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(54) Title: POLYMERIC TRANSITION METAL COMPLEXES AND USES THEREOF

(57) Abstract: Novel polymeric transition metal complexes of iron, cobalt, ruthenium, osmium, and vanadium are described. The polymeric transition metal complexes can be electron transfer mediators in enzyme-based electrochemical sensors. In such instances, transition metal complexes accept electrons from, or transfer electrons to, enzymes at a high rate and also exchange electrons rapidly with the sensor.

POLYMERIC TRANSITION METAL COMPLEXES AND USES THEREOF

This application is being filed as a PCT International Patent application in the name of TheraSense, Inc., a U.S. national corporation, on 14 November 2000, 5 designating all countries except the United States of America.

Field of the Invention

This invention relates to polymeric transition metal complexes and uses thereof including the use as redox mediators. In addition, the invention relates to transition metal complexes coupled to polymeric backbones through spacers.

10

Background of the Invention

Enzyme based electrochemical sensors are widely used in the detection of analytes in clinical, environmental, agricultural and biotechnological applications. Analytes that can be measured in clinical assays of fluids of the human body include, for example, glucose, lactate, cholesterol, bilirubin and amino acids. Levels 15 of these analytes in biological fluids, such as blood, are important for the diagnosis and the monitoring of diseases.

Electrochemical assays are typically performed in cells with two or three electrodes, including at least one measuring or working electrode and one reference electrode. In three electrode systems, the third electrode is a counter-electrode. In 20 two electrode systems, the reference electrode also serves as the counter-electrode. The electrodes are connected through a circuit, such as a potentiostat. The measuring or working electrode is a non-corroding carbon or metal conductor. Upon passage of a current through the working electrode, a redox enzyme is electrooxidized or electroreduced. The enzyme is specific to the analyte to be 25 detected, or to a product of the analyte. The turnover rate of the enzyme is typically related (preferably, but not necessarily, linearly) to the concentration of the analyte itself, or to its product, in the test solution.

The electrooxidation or electroreduction of the enzyme is often facilitated by the presence of a redox mediator in the solution or on the electrode. The redox 30 mediator assists in the electrical communication between the working electrode and

the enzyme. The redox mediator can be dissolved in the fluid to be analyzed, which is in electrolytic contact with the electrodes, or can be applied within a coating on the working electrode in electrolytic contact with the analyzed solution. The coating is preferably not soluble in water, though it may swell in water. Useful devices can 5 be made, for example, by coating an electrode with a film that includes a redox mediator and an enzyme where the enzyme is catalytically specific to the desired analyte, or its product. In contrast to a coated redox mediator, a diffusional redox mediator, which can be soluble or insoluble in water, functions by shuttling electrons between, for example, the enzyme and the electrode. In any case, when the substrate 10 of the enzyme is electrooxidized, the redox mediator transports electrons from the substrate-reduced enzyme to the electrode; when the substrate is electroreduced, the redox mediator transports electrons from the electrode to the substrate-oxidized enzyme.

Recent enzyme based electrochemical sensors have employed a number of 15 different redox mediators such as monomeric ferrocenes, quinoid-compounds including quinines (e.g., benzoquinones), nickel cyclamates, and ruthenium ammines. For the most part, these redox mediators have one or more of the following limitations: the solubility of the redox mediators in the test solutions is low, their chemical, light, thermal, or pH stability is poor, or they do not exchange 20 electrons rapidly enough with the enzyme or the electrode or both. Additionally, the redox potentials of many of these reported redox mediators are so oxidizing that at the potential where the reduced mediator is electrooxidized on the electrode, solution components other than the analyte are also electrooxidized; in other cases they are so reducing that solution components, such as, for example, dissolved oxygen are also 25 rapidly electroreduced. As a result, the sensor utilizing the mediator is not sufficiently specific.

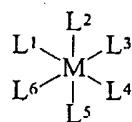
Redox mediators can be incorporated into a cross-linked redox polymer network. Such redox polymers facilitate electron transfer between the enzyme or analyte and the electrode surface. Electrons propagate from the redox polymer to the 30 electrode via electron exchanges between segments of the crosslinked polymer film. Electron exchange can occur during collisions between different segments of the

redox polymer network and can continue until the electrons reach the electrode surface.

Summary of the Invention

5 The present invention is directed to novel polymeric transition metal complexes and their use as redox polymers and redox mediators. The redox polymers are generally capable of carrying electrons between an enzyme and an electrode. The polymers can be useful in electrochemical biosensors.

10 One embodiment is a polymeric transition metal complex that includes a polymeric backbone, a plurality of spacers, and a plurality of transition metal complexes. Each of the spacers is covalently coupled to and extending from the polymeric backbone and includes at least one non-cyclic functional group selected from the group consisting of -(CR^tR^s)-, -O-, -S-, -C(O)O-, -S(O)₂NR^k-, -OC(O)NR^m-, -OC(S)NRⁿ, -C(O)NR^l-, -NR^u-, -CR^v=N-O-, -CR^w=NNR^x-, and -(SiR^yR^z)-, where R^t and R^s are independently hydrogen, chlorine, fluorine, or substituted or 15 unsubstituted alkyl, alkoxy, alkenyl, or alkynyl and R^k, R^m, Rⁿ, R^l, R^u, R^v, R^w, R^x, R^y, and R^z are independently hydrogen or substituted or unsubstituted alkyl. Each of the transition metal complexes has the formula:

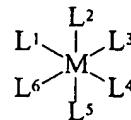


20 M is osmium, ruthenium, vanadium, cobalt, or iron. L¹ is a ligand that includes a heterocycle and is coordinatively bound to M via a heteroatom of the heterocycle. L², L³, L⁴, L⁵, and L⁶ are ligands, where each of L¹, L², L³, L⁴, L⁵, and L⁶ is independently a monodentate ligand or combined with at least one other ligand to form a multidentate ligand. At least one of L¹, L², L³, L⁴, L⁵, and L⁶ is covalently 25 coupled to one of the spacers.

Another embodiment is a polymeric transition metal complex that includes a reaction product of

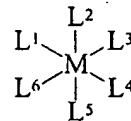
a) a polymer having a polymeric backbone and a plurality of pendant groups extending from the polymeric backbone, where at least a portion of the 30 pendant groups have a reactive group and

- b) a plurality of transition metal complexes, each transition metal complex having the formula:



M is osmium, ruthenium, vanadium, cobalt, or iron. L¹ is a ligand comprising a heterocycle and coordinatively bound to M via a heteroatom of the heterocycle. L², L³, L⁴, L⁵, and L⁶ are ligands, where each of L¹, L², L³, L⁴, L⁵, and L⁶ is independently a monodentate ligand or combined with at least one other ligand to form a multidentate ligand. At least one of L¹, L², L³, L⁴, L⁵, and L⁶ includes a reactive group that is capable of reacting with one of the reactive groups of the polymer.

Yet another embodiment is a polymeric transition metal complex that includes a polymeric backbone, a plurality of spacers, and a plurality of transition metal complexes. Each spacer is covalently coupled to and extends from the polymeric backbone and includes a flexible chain of at least four atoms. Each transition metal complex has the formula:



M is osmium, ruthenium, vanadium, cobalt, or iron. L¹ is a ligand comprising a heterocycle and coordinatively bound to M via a heteroatom of the heterocycle. L², L³, L⁴, L⁵, and L⁶ are ligands, where each of L¹, L², L³, L⁴, L⁵, and L⁶ is independently a monodentate ligand or combined to form one or more multidentate ligands. At least one of L¹, L², L³, L⁴, L⁵, and L⁶ is covalently coupled to one of the spacers.

Another embodiment of the invention is a redox mediator that includes any of the polymeric transition metal complexes described above.

Yet another embodiment is a sensor that includes the redox mediator, a working electrode, and a counter electrode. The redox mediator is disposed proximate to the working electrode. Preferably, the redox mediator is disposed on

the working electrode. More preferably, the redox mediator is non-leachably disposed on the working electrode.

Detailed Description

Generally, the present invention relates to polymeric transition metal complexes and their uses, including their use as redox mediators. In addition, the present invention relates to transition metal complexes attached to a polymeric backbone through a spacer. The invention also relates to the preparation of polymeric transition metal complexes. In at least some instances, the polymeric transition metal complexes have one or more of the following characteristics: redox potentials in a particular range and the ability to exchange electrons rapidly with electrodes and accelerate the kinetics of electrooxidation or electroreduction of an analyte in the presence of a redox enzyme or another analyte-specific redox catalyst.

When used herein, the following definitions define the stated term:

The term "alkyl" includes linear or branched, saturated aliphatic hydrocarbons. Examples of alkyl groups include methyl, ethyl, n-propyl, isopropyl, n-butyl, *tert*-butyl and the like. Unless otherwise noted, the term "alkyl" includes both alkyl and cycloalkyl groups.

The term "alkoxy" describes an alkyl group joined to the remainder of the structure by an oxygen atom. Examples of alkoxy groups include methoxy, ethoxy, n-propoxy, isopropoxy, butoxy, *tert*-butoxy, and the like. In addition, unless otherwise noted, the term 'alkoxy' includes both alkoxy and cycloalkoxy groups.

The term "alkenyl" describes an unsaturated, linear or branched aliphatic hydrocarbon having at least one carbon-carbon double bond. Examples of alkenyl groups include ethenyl, 1-propenyl, 2-propenyl, 1-butenyl, 2-methyl-1-propenyl, and the like.

A "reactive group" is a functional group of a molecule that is capable of reacting with another compound to couple at least a portion of that other compound to the molecule. Reactive groups include carboxy, activated ester, sulfonyl halide, sulfonate ester, isocyanate, isothiocyanate, epoxide, aziridine, halide, aldehyde, ketone, amine, acrylamide, thiol, acyl azide, acyl halide, hydrazine, hydroxylamine, alkyl halide, imidazole, pyridine, phenol, alkyl sulfonate, halotriazine, imido ester,

maleimide, hydrazide, hydroxy, and photo-reactive azido aryl groups. Activated esters, as understood in the art, generally include esters of succinimidyl, benzotriazolyl, or aryl substituted by electron-withdrawing groups such as sulfo, nitro, cyano, or halo groups; or carboxylic acids activated by carbodiimides.

5 A "substituted" functional group (e.g., substituted alkyl, alkenyl, or alkoxy group) includes at least one substituent selected from the following: halogen, alkoxy, mercapto, aryl, alkoxy carbonyl, alkylaminocarbonyl, dialkylaminocarbonyl, -OH, -NH₂, alkylamino, dialkylamino, trialkylammonium, alkanoylamino, arylcarboxamido, hydrazino, alkylthio, alkenyl, and reactive groups.

10 A "biological fluid" is any body fluid or body fluid derivative in which the analyte can be measured, for example, blood, interstitial fluid, plasma, dermal fluid, sweat, and tears.

An "electrochemical sensor" is a device configured to detect the presence of or measure the concentration or amount of an analyte in a sample via
15 electrochemical oxidation or reduction reactions. These reactions typically can be transduced to an electrical signal that can be correlated to an amount or concentration of analyte.

A "redox mediator" is an electron transfer agent for carrying electrons between an analyte or an analyte-reduced or analyte-oxidized enzyme and an
20 electrode, either directly, or via one or more additional electron transfer agents.

"Electrolysis" is the electrooxidation or electroreduction of a compound either directly at an electrode or via one or more electron transfer agents (e.g., redox mediators or enzymes).

The term "reference electrode" includes both a) reference electrodes and b)
25 reference electrodes that also function as counter electrodes (i.e., counter/reference electrodes), unless otherwise indicated.

The term "counter electrode" includes both a) counter electrodes and b)
counter electrodes that also function as reference electrodes (i.e., counter/reference electrodes), unless otherwise indicated.

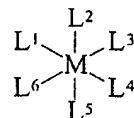
30 The term "flexible chain" refers to a saturated C4 to C24 chain where, optionally, one or more of the carbon atoms are replaced by heteroatoms (such as,

for example, oxygen, sulfur, or nitrogen) as part of, for example, an ether, thioether, or amine group. The chain can be substituted or unsubstituted.

Polymeric Transition Metal Complexes

The polymeric transition metal complex includes a polymeric backbone, spacers covalently coupled to and extending from the polymeric backbone, and transition metal complexes, each having at least one ligand that is covalently coupled to one of the spacers. Examples of suitable transition metal complexes include those described in U.S. Patents Nos. 5,262,035, 5,262,305, 5,320,725, 5,365,786, 5,378,628, 5,393,903, 5,593,852, 5,665,222, 5,972,199, and 6,143,164, U.S. Patent Applications Serial Nos. 09/034,372, 09/070,677, 09/295,962, and 09/434,026, U.S. Provisional Patent Application Serial No. 60/165,565, and U.S. Patent Application Serial No. _____, entitled "Transition Metal Complexes with Bidentate Ligand having an Imidazole Ring", Attorney Docket No. 12008.41US01, filed on even date herewith, all of which are incorporated herein by reference.

Typically, each of the transition metal complexes has the formula:



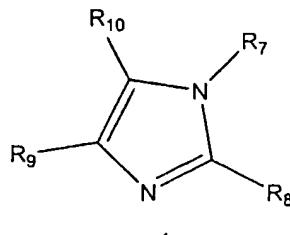
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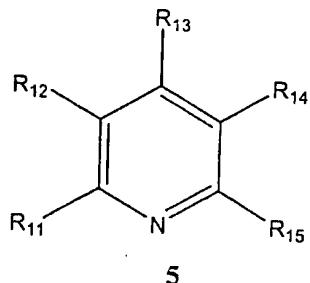
M is a transition metal and is typically osmium, ruthenium, vanadium, cobalt, or iron. L^1 , L^2 , L^3 , L^4 , L^5 , and L^6 are ligands and are independently monodentate ligands or two or more of the ligands can be combined to form one or more multidentate ligands. L^1 , in particular, is a ligand that includes a heterocycle and is coordinatively bound to M via a heteroatom of the heterocycle. At least one of L^1 , L^2 , L^3 , L^4 , L^5 , and L^6 is covalently coupled to one of the spacers.

Any combination of monodentate and multidentate ligands can be used. For example, L^1 , L^2 , L^3 , L^4 , L^5 , and L^6 can combine to form three bidentate ligands such as, for example, three bidentate ligands selected from substituted and unsubstituted 2,2'-biimidazoles, 2-(2-pyridyl)imidazoles, and 2,2'-bipyridines. Examples of other combinations of L^1 , L^2 , L^3 , L^4 , L^5 , and L^6 include:

- (A) Two monodentate ligands and two bidentate ligands;
(B) Four monodentate ligands and one bidentate ligand;
(C) Three monodentate ligands and one tridentate ligand;
(D) One monodentate ligand, one bidentate ligand, and one tridentate
5 ligand;
(E) Two monodentate ligands and one tetridentate ligand; and
(F) One bidentate ligand and one tetridentate ligand.

Examples of suitable monodentate ligands include, but are not limited to, -F, -Cl, -Br, -I, -CN, -SCN, -OH, H₂O, NH₃, alkylamine, dialkylamine, trialkylamine, alkoxy or heterocyclic compounds. The alkyl or aryl portions of any of the ligands 10 are optionally substituted by -F, -Cl, -Br, -I, alkylamino, dialkylamino, trialkylammonium (except aryl portions), alkoxy, alkylthio, aryl, or a reactive group. Any alkyl portions of the monodentate ligands generally contain 1 to 12 carbons. More typically, the alkyl portions contain 1 to 6 carbons. In other embodiments, the 15 monodentate ligands are heterocyclic compounds containing at least one nitrogen, oxygen, or sulfur atom. Examples of suitable heterocyclic monodentate ligands include imidazole, pyrazole, oxazole, thiazole, pyridine, pyrazine and derivatives thereof. Suitable heterocyclic monodentate ligands include substituted and unsubstituted imidazole and substituted and unsubstituted pyridine having the 20 following general formulas 4 and 5, respectively:





With regard to formula 4, R₇ is generally a substituted or unsubstituted alkyl, alkenyl, or aryl group. Typically, R₇ is a substituted or unsubstituted C1 to C12 alkyl or alkenyl. The substitution of inner coordination sphere chloride anions by imidazoles does not typically cause a large shift in the redox potential in the oxidizing direction, differing in this respect from substitution by pyridines, which typically results in a large shift in the redox potential in the oxidizing direction.

- R₈, R₉ and R₁₀ are independently -H, -F, -Cl, -Br, -I, -NO₂, -CN, -CO₂H, -SO₃H, -NNNH₂, -SH, aryl, alkoxy carbonyl, alkylaminocarbonyl, dialkylaminocarbonyl, -OH, alkoxy, -NH₂, alkylamino, dialkylamino, alkanoylamino, arylcarboxamido, hydrazino, alkylhydrazino, hydroxylamino, alkoxy lamino, alkylthio, alkenyl, aryl, or alkyl. Alternatively, R₈ and R₁₀, in combination, form a fused 5 or 6-membered ring that is saturated or unsaturated.
- The alkyl portions of the substituents generally contain 1 to 12 carbons and typically contain 1 to 6 carbon atoms. The alkyl or aryl portions of any of the substituents are optionally substituted by -F, -Cl, -Br, -I, alkylamino, dialkylamino, trialkylammonium (except aryl portions), alkoxy, alkylthio, aryl, or a reactive group. In some embodiments, R₈, R₉ and R₁₀ are -H or substituted or unsubstituted alkyl.
- Preferably, R₈, R₉ and R₁₀ are -H.

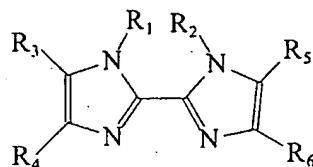
With regard to Formula 5, R₁₁, R₁₂, R₁₃, R₁₄ and R₁₅ are independently -H, -F, -Cl, -Br, -I, -NO₂, -CN, -CO₂H, alkoxy carbonyl, alkylaminocarbonyl, dialkylaminocarbonyl, -OH, alkoxy, -NH₂, alkylamino, dialkylamino, alkanoylamino, arylcarboxamido, hydrazino, alkylhydrazino, hydroxylamino, alkoxy lamino, alkylthio, alkenyl, aryl, or alkyl. The alkyl or aryl portions of any of the substituents are optionally substituted by -F, -Cl, -Br, -I, alkylamino,

dialkylamino, trialkylammonium (except aryl portions), alkoxy, alkylthio, aryl, or a reactive group. Generally, R₁₁, R₁₂, R₁₃, R₁₄ and R₁₅ are -H, methyl, C1-C2 alkoxy, C1-C2 alkylamino, C2-C4 dialkylamino, or a C1-C6 lower alkyl substituted with a reactive group.

- 5 One example includes R₁₁ and R₁₅ as -H, R₁₂ and R₁₄ as the same and -H or methyl, and R₁₃ as -H, C1 to C12 alkoxy, -NH₂, C1 to C12 alkylamino, C2 to C24 dialkylamino, hydrazino, C1 to C12 alkylhydrazino, hydroxylamino, C1 to C12 alkoxyamino, C1 to C12 alkylthio, or C1 to C12 alkyl. The alkyl or aryl portions of any of the substituents are optionally substituted by -F, -Cl, -Br, -I, alkylamino, 10 dialkylamino, trialkylammonium (except aryl portions), alkoxy, alkylthio, aryl, or a reactive group.

Examples of suitable bidentate ligands include, but are not limited to, amino acids, oxalic acid, acetylacetone, diaminoalkanes, ortho-diaminoarenes, 2,2'-biimidazole, 2,2'-bioxazole, 2,2'-bithiazole, 2-(2-pyridyl)imidazole, and 2,2'-bipyridine and derivatives thereof. Particularly suitable bidentate ligands for redox mediators include substituted and unsubstituted 2,2'-biimidazole, 2-(2-pyridyl)imidazole and 2,2'-bipyridine.

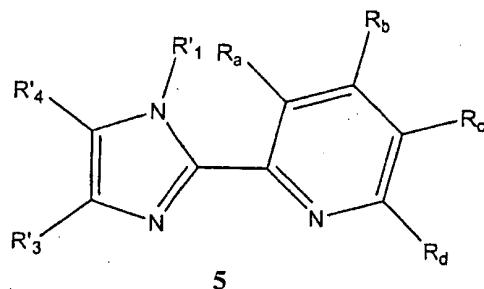
15 Examples of 2,2'-biimidazole ligands are illustrated by Formula 4.



- R₁ and R₂ are substituents attached to two of the 2,2'-biimidazole nitrogens and are independently substituted or unsubstituted alkyl, alkenyl, or aryl groups. Generally, R₁ and R₂ are unsubstituted C1 to C12 alkyls. Typically, R₁ and R₂ are unsubstituted C1 to C4 alkyls. In some embodiments, both R₁ and R₂ are methyl.
- 25 R₃, R₄, R₅, and R₆ are substituents attached to carbon atoms of the 2,2'-biimidazole and are independently -H, -F, -Cl, -Br, -I, -NO₂, -CN, -CO₂H, -SO₃H, alkoxy carbonyl, alkylaminocarbonyl, dialkylaminocarbonyl, -OH, alkoxy, -NH₂, alkylamino, dialkylamino, alkanoylamino, arylcarboxamido, hydrazino, alkylhydrazino, hydroxylamino, alkoxyamino, alkylthio, alkenyl, aryl, or alkyl.

Alternatively, R₃ and R₄ in combination or R₅ and R₆ in combination independently form a saturated or unsaturated 5- or 6-membered ring. An example of this is a 2,2'-bibenzoimidazole derivative. Typically, the alkyl and alkoxy portions are C1 to C12. The alkyl or aryl portions of any of the substituents are optionally substituted by -F, -Cl, -Br, -I, alkylamino, dialkylamino, trialkylammonium (except aryl portions), alkoxy, alkylthio, aryl, or a reactive group. Generally, R₃, R₄, R₅, and R₆ are independently -H or unsubstituted alkyl groups. Typically, R₃, R₄, R₅, and R₆ are -H or unsubstituted C1 to C12 alkyls. In some embodiments, R₃, R₄, R₅, and R₆ are all -H.

Examples of 2-(2-pyridyl)imidazoles have the following general formula 5:



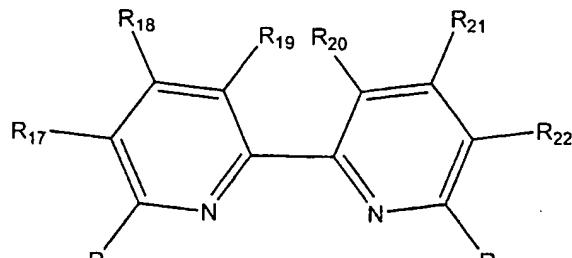
R'₁ is a substituted or unsubstituted aryl, alkenyl, or alkyl. Generally, R'₁ is a substituted or unsubstituted C1-C12 alkyl. R'₁ is typically methyl or a C1-C12 alkyl that is optionally substituted with a reactive group.

R'₃, R'₄, R_a, R_b, R_c, and R_d are independently -H, -F, -Cl, -Br, -I, -NO₂, -CN, -CO₂H, -SO₃H, -NHNH₂, -SH, alkoxy carbonyl, alkylaminocarbonyl, dialkylaminocarbonyl, -OH, alkoxy, -NH₂, alkylamino, dialkylamino, alkanoylamino, arylcarboxamido, hydrazino, alkylhydrazino, hydroxylamino, alkoxy lamino, alkylthio, alkenyl, aryl, or alkyl. Alternatively, R_c and R_d in combination or R'₃ and R'₄ in combination can form a saturated or unsaturated 5- or 6-membered ring. Typically, the alkyl and alkoxy portions are C1 to C12. The alkyl or aryl portions of any of the substituents are optionally substituted by -F, -Cl, -Br, -I, alkylamino, dialkylamino, trialkylammonium (except aryl portions), alkoxy, alkylthio, aryl, or a reactive group. Generally, R'₃, R'₄, R_a, R_b, R_c and R_d are

independently -H or unsubstituted alkyl groups. Typically, R_a and R_c are -H and R'₃, R'₄, R_b, and R_d are -H or methyl.

Examples of 2,2'-bipyridine ligands have the following general formula 6:

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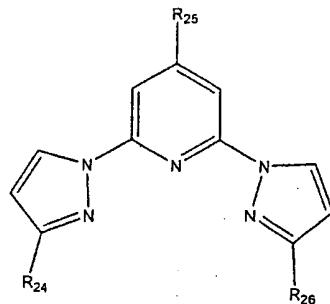
R₁₆, R₁₇, R₁₈, R₁₉, R₂₀, R₂₁, R₂₂ and R₂₃ are independently -H, -F, -Cl, -Br, -I, -NO₂, -CN, -CO₂H, -SO₃H, -NHNH₂, -SH, aryl, alkoxy carbonyl, alkylaminocarbonyl, dialkylaminocarbonyl, -OH, alkoxy, -NH₂, alkylamino, 10 dialkylamino, alkanoylamino, arylcarboxamido, hydrazino, alkylhydrazino, hydroxylamino, alkoxy lamino, alkylthio, alkenyl, or alkyl. Typically, the alkyl and alkoxy portions are C1 to C12. The alkyl or aryl portions of any of the substituents are optionally substituted by -F, -Cl, -Br, -I, alkylamino, dialkylamino, trialkylammonium (except aryl portions), alkoxy, alkylthio, aryl, or a reactive group.

15 Specific examples of suitable combinations of R₁₆, R₁₇, R₁₈, R₁₉, R₂₀, R₂₁, R₂₂ and R₂₃ include R₁₆ and R₂₃ as H or methyl; R₁₇ and R₂₂ as the same and -H or methyl; and R₁₉ and R₂₀ as the same and -H or methyl. An alternative combination is where one or more adjacent pairs of substituents R₁₆ and R₁₇, on the one hand, and R₂₂ and R₂₃, on the other hand, independently form a saturated or unsaturated 5- or 6-20 membered ring. Another combination includes R₁₉ and R₂₀ forming a saturated or unsaturated five or six membered ring.

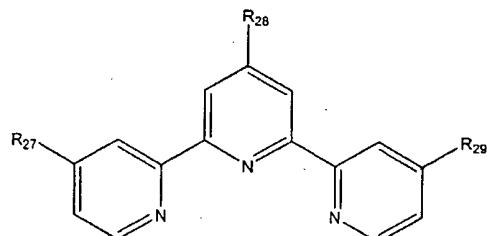
Another combination includes R₁₆, R₁₇, R₁₉, R₂₀, R₂₂ and R₂₃ as the same and -H and R₁₈ and R₂₁ as independently -H, alkoxy, -NH₂, alkylamino, dialkylamino, alkylthio, alkenyl, or alkyl. The alkyl or aryl portions of any of the substituents are 25 optionally substituted by -F, -Cl, -Br, -I, alkylamino, dialkylamino, trialkylammonium (except aryl portions), alkoxy, alkylthio, aryl, or a reactive group. As an example, R₁₈ and R₂₁ can be the same or different and are -H, C1-C6 alkyl,

C1-C6 amino, C1 to C12 alkylamino, C2 to C12 dialkylamino, C1 to C12 alkylthio, or C1 to C12 alkoxy, the alkyl portions of any of the substituents are optionally substituted by a -F, -Cl, -Br, -I, aryl, C2 to C12 dialkylamino, C3 to C18 trialkylammonium, C1 to C6 alkoxy, C1 to C6 alkylthio or a reactive group.

5 Examples of suitable terdentate ligands include, but are not limited to, diethylenetriamine, 2,2',2"-terpyridine, 2,6-bis(N-pyrazolyl)pyridine, and derivatives of these compounds. 2,2',2"-terpyridine and 2,6-bis(N-pyrazolyl)pyridine have the following general formulas 7 and 8 respectively:



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With regard to formula 7, R₂₄, R₂₅ and R₂₆ are independently -H or substituted or unsubstituted C1 to C12 alkyl. Typically, R₂₄, R₂₅ and R₂₆ are -H or methyl and, in some embodiments, R₂₄ and R₂₆ are the same and are -H. Other substituents at these or other positions of the compounds of formulas 7 and 8 can be added.

15

With regard to formula 8, R₂₇, R₂₈ and R₂₉ are independently -H, -F, -Cl, -Br, -I, -NO₂, -CN, -CO₂H, -SO₃H, -NHNH₂, -SH, alkoxy carbonyl, alkylaminocarbonyl, dialkylaminocarbonyl, -OH, alkoxy, -NH₂, alkylamino, dialkylamino, alkanoylamino, arylcarboxamido, hydrazino, alkylhydrazino, hydroxylamino,

alkoxylamino, alkylthio, alkenyl, aryl, or alkyl. The alkyl or aryl portions of any of the substituents are optionally substituted by -F, -Cl, -Br, -I, alkylamino, dialkylamino, trialkylammonium (except aryl portions), alkoxy, alkylthio, aryl, or a reactive group. Typically, the alkyl and alkoxy groups are C1 to C12 and, in some 5 embodiments, R₂₇ and R₂₉ are the same and are -H.

Examples of suitable tetradentate ligands include, but are not limited to, triethylenetriamine, ethylenediaminediacetic acid, tetraaza macrocycles and similar compounds as well as derivatives thereof.

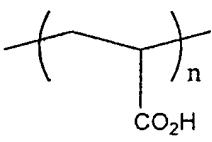
In some embodiments, the transition metal complexes are positively charged 10 (e.g., with a charge ranging from +1 to +5). The complexes can, alternatively, be negatively charged (e.g., with a charge ranging from -1 to -5), for example, when the ligands or the backbone are derivatized with a sufficient number of negatively charged functional groups such as carboxylate, phosphate or sulfonate functions. One or more counter ions can be used to balance the charge. Examples of suitable 15 counter ions include anions, such as halide (e.g., fluoride, chloride, bromide or iodide), sulfate, phosphate, hexafluorophosphate, and tetrafluoroborate, and cations (preferably, monovalent cations), such as lithium, sodium, potassium, tetralkylammonium, and ammonium.

In some embodiments, a transition metal complex precursor includes a 20 substituent containing a reactive group extending from one of the ligands. This reactive group can react with a reactive group disposed on a precursor polymer to couple the transition metal complex precursor to the polymer to form the polymeric transition metal complex.

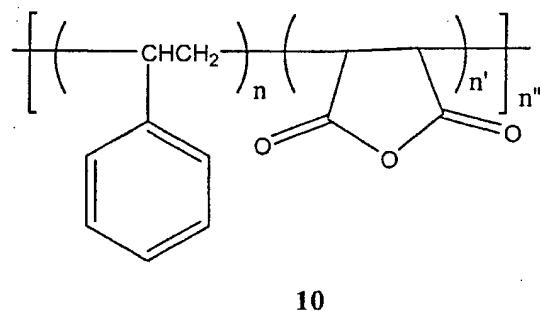
Generally, any polymeric backbone can be used. Typically, as a precursor to 25 forming the polymeric transition metal complex, a precursor polymer with pendant groups extending from a polymeric backbone is used. At least some of the pendant groups are used to form, at least a portion of the spacers. Preferably, at least some of the pendant groups of the precursor polymer, prior to attachment to the transition metal complex, have a reactive group attached to the pendant groups. The reactive 30 group can be part of the original polymer or can be added to the polymer, for example, by reaction or quaternization of a nitrogen-containing heterocyclic ring. Examples of suitable polymeric backbones include partially or fully quaternized

poly(4-vinylpyridine) and poly(N-vinylimidazole) in which quaternized pyridine and imidazole groups, respectively, can be used to form spacers by reaction with (e.g., complexation with) a transition metal complex. Other suitable precursor polymers include, for example, poly(acrylic acid) (Formula 9), styrene/maleic anhydride copolymer (Formula 10), methylvinylether/maleic anhydride copolymer (GANTREZ polymer) (Formula 11), poly(vinylbenzylchloride) (Formula 12), poly(allylamine) (Formula 13), polylysine (Formula 14), poly(4-vinylpyridine) quaternized with carboxypentyl groups (Formula 15), and poly(sodium 4-styrene sulfonate) (Formula 16).

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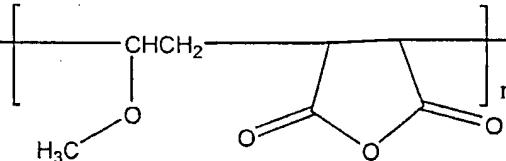


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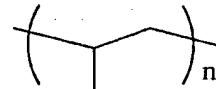


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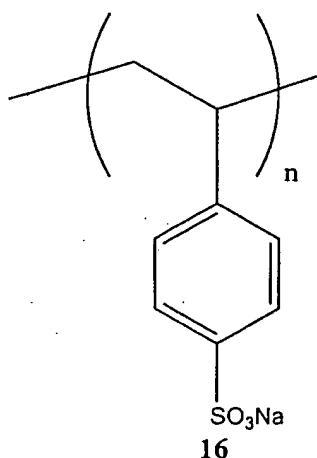
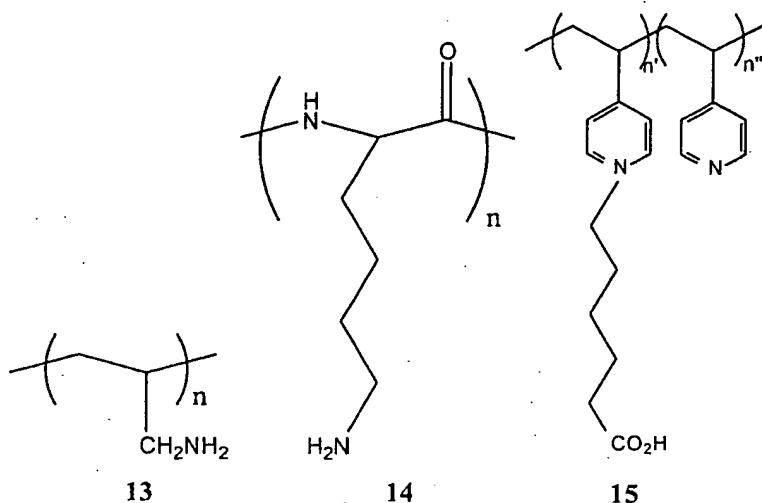


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- The spacer couples the transition metal complex to the polymeric backbone. In some embodiments, the spacer includes at least one non-cyclic functional group selected from the group consisting of -(CR^rR^s)-, -O-, -S-, -C(O)O-, -S(O)₂NR^k-, -OC(O)NR^m-, -OC(S)NRⁿ-, -C(O)NR^l-, -NR^u-, -CR^v=N-O-, -CR^w=NNR^x-, and -
 10 (SiR^yR^z)-, where R^r and R^s are independently hydrogen, chlorine, fluorine, or substituted or unsubstituted alkyl, alkoxy, alkenyl, or alkynyl and R^k, R^m, Rⁿ, R^l, R^u, R^v, R^w, R^x, R^y, and R^z are independently hydrogen or substituted or unsubstituted alkyl. Preferably, the spacer includes at least four, and, more preferably, at least eight of these non-cyclic functional groups. Preferably, the non-cyclic functional
 15 group(s) is/are selected from the group consisting of -(CR^rR^s)-, -O-, -S-, -S(O)₂NR^k-,

-OC(O)NR^m-, -OC(S)NRⁿ, -C(O)NR^t-, and -NR^u-, where R^k, R^m, Rⁿ, R^t, R^s, R^l, and R^u are independently selected from the group consisting of hydrogen and substituted or unsubstituted alkyl. In one embodiment, the preferred spacer includes a 4 to 30 atom long linear segment, the linear segment having any combination of the following bonds to form the 4 to 30 atom chain of the segment: C-C, C-N, C-O, C-Si, C-S, S-N, and Si-O.

The spacer is typically a reaction product of a precursor polymer having a pendant group with a reactive group attached thereto and a transition metal complex having a reactive group extending from one of the ligands. Typically, one of the reactive groups is an electrophile and the other reactive group is a nucleophile. Selected examples of reactive groups and the linkages formed from their interactions are shown in Table 1.

Table 1: Examples of Reactive Group Linkages

First Reactive Group	Second Reactive Group	Resulting Linkage
Activated ester*	Amine	Amide
Acrylamide	Thiol	Thioether
Acyl azide	Amine	Amide
Acyl halide	Amine	Amide
Carboxylic acid	Amine	Amide
Aldehyde or ketone	Hydrazine	Hydrazone
Aldehyde or ketone	Hydroxyamine	Oxime
Alkyl halide	Amine	Alkylamine
Alkyl halide	Carboxylic acid	Ester
Alkyl halide	Imidazole	Imidazolium
Alkyl halide	Pyridine	Pyridinium
Alkyl halide	Alcohol/phenol	Ether
Alkyl halide	Thiol	Thioether
Alkyl sulfonate	Thiol	Thioether
Alkyl sulfonate	Pyridine	Pyridinium
Alkyl sulfonate	Imidazole	Imidazolium
Alkyl sulfonate	Alcohol/phenol	Ether
Anhydride	Alcohol/phenol	Ester
Anhydride	Amine	Amide
Aziridine	Thiol	Thioether
Aziridine	Amine	Alkylamine
Aziridine	Pyridine	Pyridinium
Epoxide	Thiol	Thioether
Epoxide	Amine	Alkylamine
Epoxide	Pyridine	Pyridinium
Halotriazine	Amine	Aminotriazine
Halotriazine	Alcohol	Triazinyl ether
Imido ester	Amine	Amidine
Isocyanate	Amine	Urea
Isocyanate	Alcohol	Urethane
Isothiocyanate	Amine	Thiourea
Maleimide	Thiol	Thioether
Sulfonyl halide	Amine	Sulfonamide

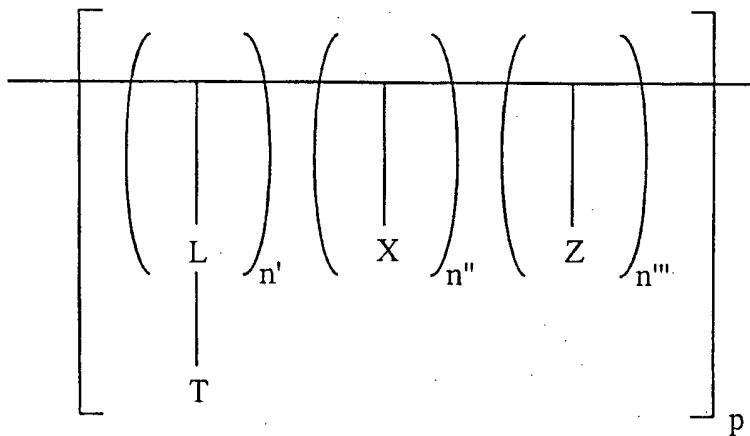
* Activated esters, as understood in the art, generally include esters of succinimidyl, benzotriazolyl, or aryl substituted by electron-withdrawing groups such as sulfo, nitro, cyano, or halo; or carboxylic acids activated by carbodiimides.

In some embodiments, the spacer includes a flexible linear chain of at least 5 four atoms. Preferably, the flexible linear chain includes at least six or eight atoms, but less than about 30 atoms. More preferably, the number of atoms forming the

flexible linear chain ranges from 8 to 18. In some instances, two or more flexible chains are included in the spacer. The flexible chain typically permits the spacer to move relative to the polymeric backbone, thereby allowing the transition metal complex on the end of the spacer to move. This is particularly useful for polymeric transition metal complexes that are used as redox mediators because the movement of the transition metal complex coupled by the spacer to the polymer backbone can facilitate transfer of electrons between transition metal complexes and with the electrode. This can enhance the electron transfer rate and can facilitate the desired electrochemical reaction at the electrode by, for example, improving the conduction of electrons by the crosslinked and hydrated polymer on the electrode.

In addition to the chains, the spacer can contain one or more other unsaturated groups. For example, the spacer can include an unsaturated functional group such as those listed in Table 1 under the heading "Resulting Linkage". As another example, the spacer can include a heterocycle or aryl group. For example, the spacer group of poly(4-vinylpyridine) or poly(N-vinylimidazole) would include a pyridine or imidazole functional group. In these specific instances, the heterocycle or aryl group is positioned between the flexible chain and the polymeric backbone, although this is not necessary to the invention.

Formula 17 schematically represent examples of the polymeric transition metal complexes of the present invention.



In general, the polymeric transition metal complex has a polymeric backbone with one or more types of pendant groups (represented in Formula 17 as L-T, X, and Z, respectively). The individual pendant groups, L-T, X, and Z, of each polymer unit can be ordered in any configuration. The number of polymer units is represented by p,
5 which is an integer having a value of one or more. The product of p and ($n' + n'' + n'''$) is generally at least 5, preferably, at least 10, and can be 50 or more.

T is a transition metal complex as described above. L is a spacer group, as described above, and couples the transition metal complex, T, to the polymeric backbone. The number of spacer group-transition metal complex units (L-T)
10 attached to the polymer backbone in each polymer unit is represented by n', which is an integer having a value of one or more.

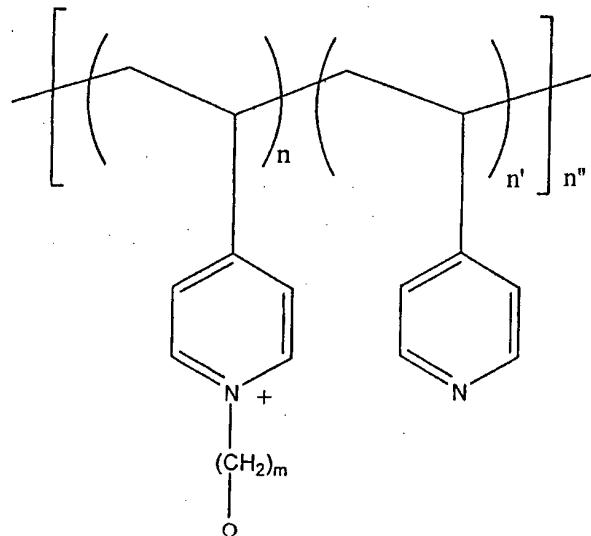
X represents a pendant group that does not contain a reactive substituent. The number of these pendant groups attached to the polymer backbone in each polymer unit is represented by n'', which is an integer having a value of zero or
15 more.

Z represents a pendant group substituted with a reactive substituent that includes, but is not limited to, pyridyl, imidazolyl, carboxy, activated ester, sulfonyl halide, sulfonate ester, isocyanate, isothiocyanate, epoxide, aziridine, halide, aldehyde, ketone, amine, acrylamide, thiol, acyl azide, acyl halide, hydrazine,
20 hydroxylamine, alkyl halide, imidazole, pyridine, phenol, alkyl sulfonate, halotriazine, imido ester, maleimide, hydrazide, hydroxy, and photo-reactive azido aryl groups. The pendant group, Z, can be used for cross-linking the polymer backbone during, for example, polymer immobilization on a surface. The number of these pendant groups attached to the polymer backbone in each polymer unit is
25 represented by n''', which is an integer having a value of zero or more.

The polymeric transition metal complex typically has a weight average molecular weight of at least 5000, although in some instances lower molecular weight polymeric transition metal complexes can be used. The weight average molecular weight of the polymeric transition metal complex can be at least 10,000,
30 50,000, 100,000, or more and can depend on the application. This weight average molecular weight generally refers to the weight average molecular weight prior to crosslinking to form a film.

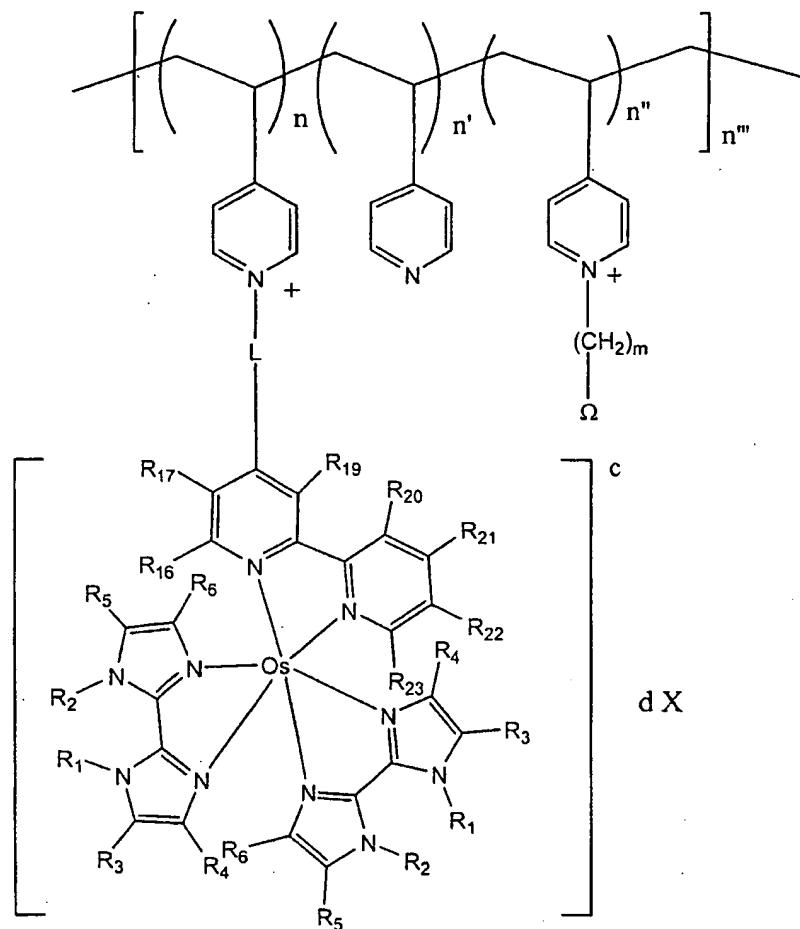
An example of a precursor polymer that can be used to form a polymeric transition metal complex is presented as Formula 18. This precursor polymer is poly(4-vinylpyridine) quaternized with an alkyl moiety substituted with a reactive group.

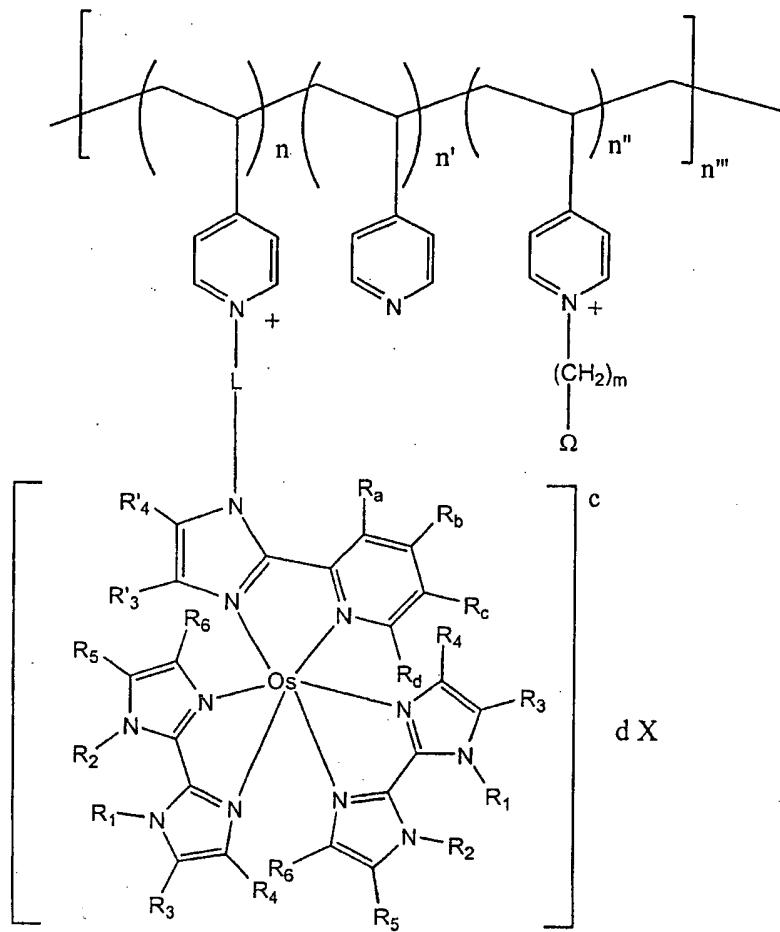
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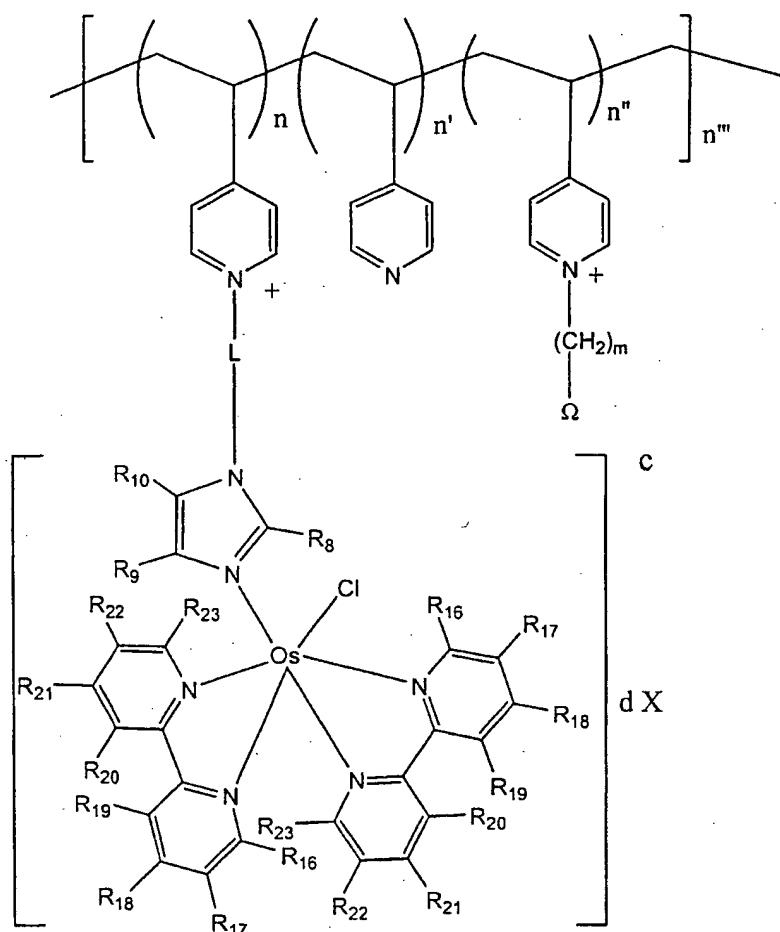
where Ω is the reactive group, m is typically 1 to 18, n and n' are the average numbers of pyridinium and pyridine subunits respectively in each repeating polymer unit, and n'' is the number of repeating polymer units.

Examples of polymeric transition metal complexes formed using this
10 precursor polymer are illustrated by Formulas 19, 20 and 21:





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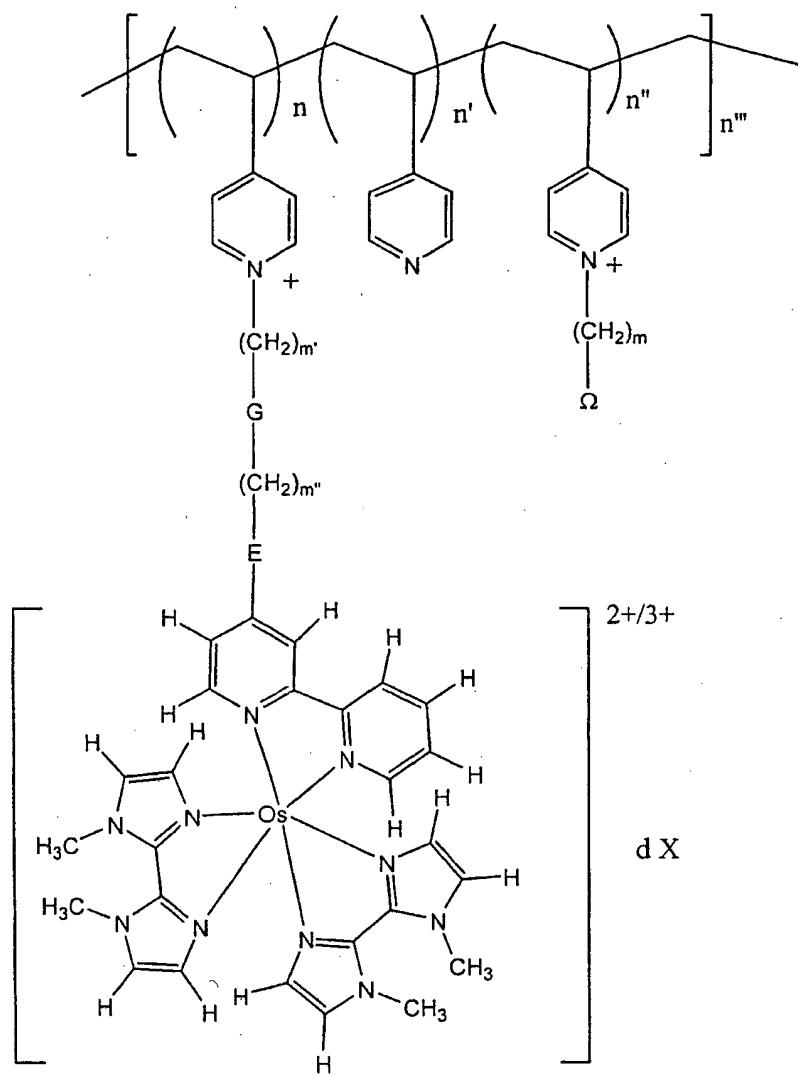


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where Ω is the reactive group; m is 1 to 18; L is the spacer, as described above,
 5 formed by the reaction of the transition metal complex to the Ω ; X represents
 counter ions; d represents the number of counter ions; c is an integer representing the
 charge of the complex; and $R_1, R_2, R_3, R_3, R_4, R_5, R_6, R_8, R_9, R_{10}, R_{16}, R_{17}, R_{18}, R_{19},$
 $R_{20}, R_{21}, R_{22}, R_{23}, R'_3, R'_4, R_a, R_b, R_c$, and R_d are as described above.

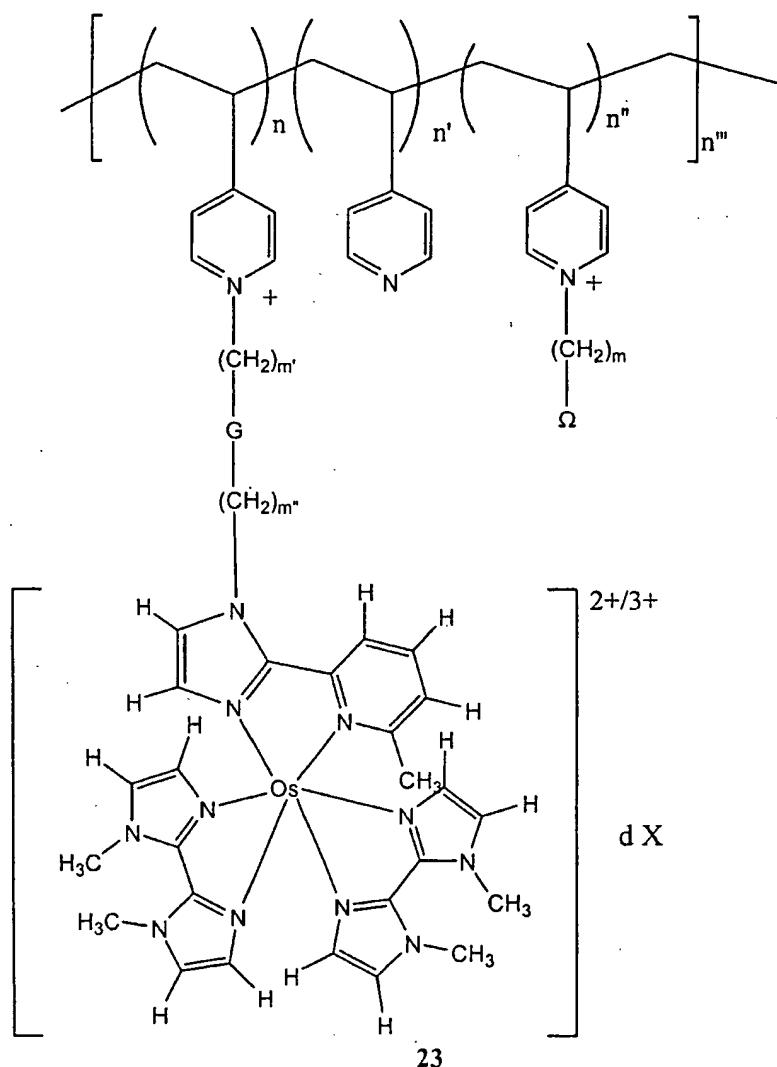
Specific examples of suitable polymeric transition metal complexes are
 10 illustrated in Formulas 22, 23, and 24.

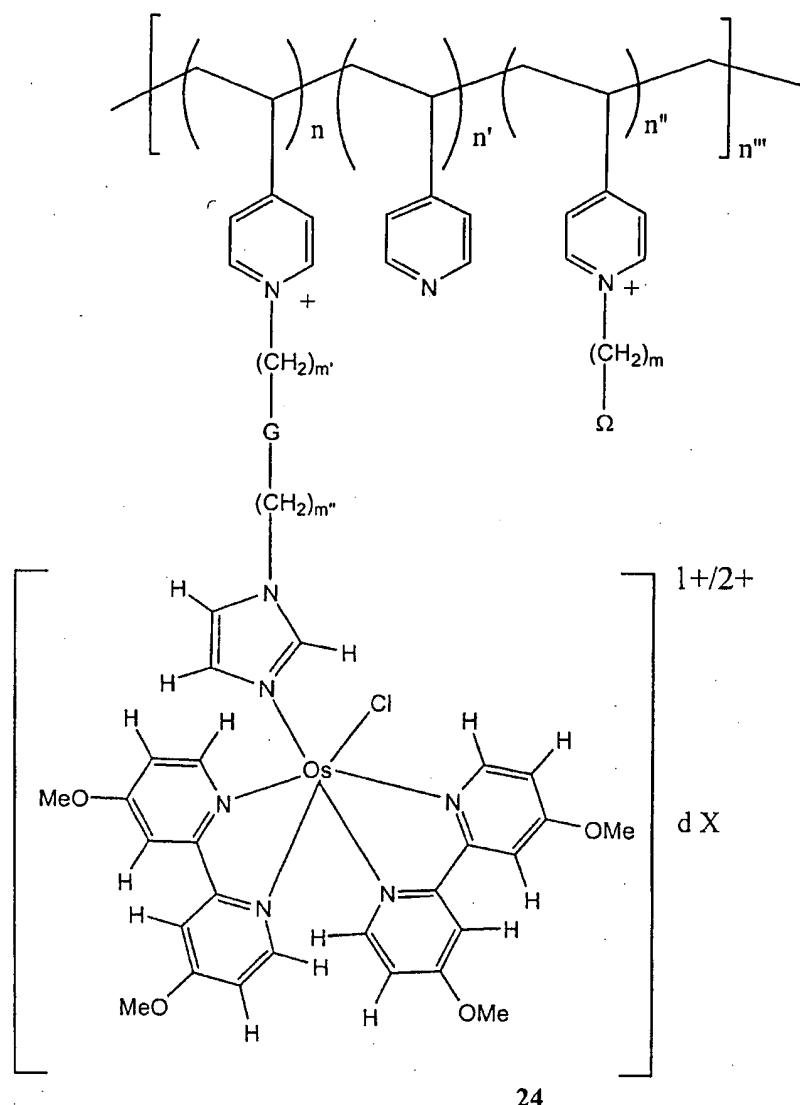
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where G represents one of the "Resulting Linkages" of Table 1 such as, for example, an amide having the formula: $-\text{CONR}_{30}-$ or $-\text{NR}_{30}\text{CO}-$, where R_{30} is a hydrogen, 5 methyl, ethyl or other 1 to 6 carbon alkyl. E is O, S or NR_{31} , where R_{31} is hydrogen, methyl, ethyl or other 1 to 6 carbon alkyl. m' and m are the same and are typically in the range of 1 to 18 and m'' is independently in the range of 1 to 18.

Polymeric transition metal complexes of the present invention can be soluble in water or other aqueous solution. However, it is envisioned that certain metal 10 complexes can be formed having some level of solubility in non-aqueous solutions.

Preferably, the solubility of transition metal complexes of the present invention is greater than about 0.1 M (moles/liter) at 25 °C.

The polymeric transition metal complexes discussed above can be useful as redox mediators in electrochemical sensors for the detection of analytes in biofluids. The use of transition metal complexes as redox mediators is described, for example, in U.S. Patents Nos. 5,262,035, 5,262,305, 5,320,725, 5,365,786, 5,593,852, 5,665,222, 5,972,199, and 6,143,164 and U.S. Patent Applications Serial Nos. 09/034,372, 09/070,677, 09/295,962, and 09/434,026, all of which are herein incorporated by reference. The polymeric transitional metal complexes described herein can typically be used in place of those discussed in the references listed above.

In general, the redox mediator is disposed on or in proximity to (e.g., in a solution surrounding) a working electrode. The redox mediator transfers electrons between the working electrode and an analyte. In some embodiments, an enzyme is also included to facilitate the transfer. For example, the redox mediator can transfer electrons between the working electrode and glucose in an enzyme-catalyzed reaction of glucose. Polymeric redox mediators are particularly useful for forming non-leachable coatings on the working electrode by, for example, crosslinking the redox mediator on the electrode.

Transition metal complexes can enable accurate, reproducible and quick or continuous assays. Transition metal complex redox mediators accept electrons from, or transfer electrons to, enzymes at a high rate and also exchange electrons rapidly with an electrode. Typically, the rate of their self exchange, the process in which a reduced redox mediator transfers an electron to an oxidized redox mediator, is rapid. At a defined redox mediator concentration, this provides for more rapid transport of electrons between the enzyme and electrode, and thereby shortens the response time of the sensor. Additionally, transition metal complex redox mediators can be stable under ambient light and at temperatures encountered in their use, storage and transportation. Preferably, the transition metal complex redox mediators do not undergo substantial chemical change, other than oxidation and reduction, in the period of their use or under the conditions of their storage, though they may be designed to be activated by reacting, for example, with water or the analyte.

The transition metal complex can be used as a redox mediator in combination with an enzyme to electrooxidize or electroreduce the analyte. The redox potentials of the redox mediators are generally more positive (i.e. more oxidizing) than the redox potentials of the enzymes when the analyte is electrooxidized and more negative when the analyte is electroreduced. For example, the redox potentials of the most preferred transition metal complex redox mediators used for electrooxidizing glucose with glucose oxidase or PQQ-glucose dehydrogenase as enzyme is between - 200 mV and + 200 mV versus a Ag/AgCl reference electrode.

10 Crosslinking in Polymeric Transition Metal Complexes

Electron transport involves an exchange of electrons between segments of the redox polymer(s) (e.g., one or more transition metal complexes coupled to a polymeric backbone, as described above) in a crosslinked film disposed on an electrode. The transition metal complex can be bound to the polymer backbone though covalent, coordinative or ionic bonds, where covalent and coordinative binding are preferred. Electron exchange occurs, for example, through the collision of different segments of the crosslinked redox polymer film. Electrons transported through the transition metal complex polymer can originate from, for example, electrooxidation of an enzymatic substrate, such as, for example, the oxidation of glucose by glucose oxidase.

The degree of crosslinking of the redox polymer can influence the transport of electrons or ions and thereby the rates of the electrochemical reactions. Excessive crosslinking of the polymer can reduce the mobility of the segments of the redox polymer. A reduction in segment mobility can slow the diffusion of electrons or ions through the redox polymer film. A reduction in the diffusivity of electrons, for example, can require a concomitant reduction in the thickness of the film on the electrode where electrons or electron vacancies are collected or delivered. When the analyte or its product is electrooxidized the electrons that are collected typically originate in the substrate of the enzyme. The degree of crosslinking in a redox polymer film can thus affect the transport of electrons from, for example, an enzyme to the transition metal redox centers of the redox polymer such as, for example,

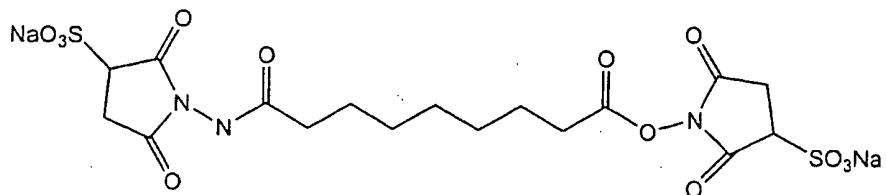
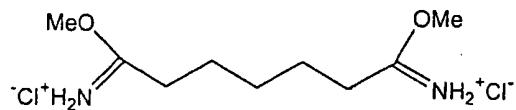
Os^{2+/3+} metal redox centers; between redox centers of the redox polymer; and from these transition metal redox centers to the electrode.

Inadequate crosslinking of a redox polymer can result in excessive swelling of the redox polymer film and to the leaching of the components of the redox polymer film. Excessive swelling can also result in the migration of the swollen polymer into the analyzed solution, in the softening of the redox polymer film, to the film's susceptibility to removal by shear, or any combination of the three effects.

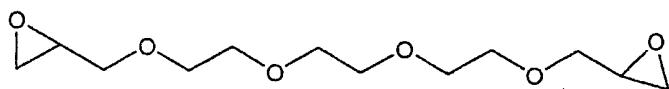
Crosslinking can decrease the leaching of film components and can improve the mechanical stability of the film under shear stress. For example, as disclosed in 10 Binyamin, G. and Heller, A; *Stabilization of Wired Glucose Oxidase Anodes Rotating at 1000 rpm at 37 °C*; Journal of the Electrochemical Society, 146(8), 2965-2967, 1999, herein incorporated by reference, replacing a difunctional crosslinker, such as polyethylene glycol diglycidyl ether, with a trifunctional crosslinker such as *N,N*-diglycidyl-4-glycidyloxyaniline, for example can reduce 15 leaching and shear problems associated with inadequate crosslinking.

Examples of other bifunctional, trifunctional and tetrafunctional crosslinkers are listed below:

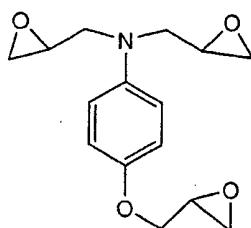
Amine-reactive Bifunctional Crosslinkers



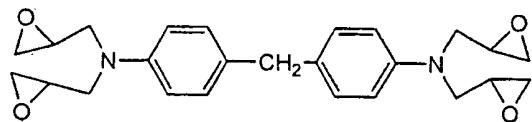
Pyridine- or Imidazole-reactive Bifunctional Crosslinkers



Pyridine- or Imidazole-reactive trifunctional Crosslinker



Pyridine- or Imidazole-reactive Tetrafunctional Crosslinkers



Alternatively, the number of crosslinking sites can be increased by reducing the number of transition metal complexes attached to the polymeric backbone, thus

making more polymer pendant groups available for crosslinking. One important advantage of at least some of the polymeric transition metal complexes is the increased mobility of the pendant transition metal complex functions, resulting of the flexibility of the spacer group L. As a result, in at least some embodiments, 5 fewer metal complex molecules per polymer backbone are needed to achieve a desired level of diffusivity of electrons and current density of analyte electrooxidation or electroreduction.

Coordination in Polymeric Transition Metal Complexes

10 Transition metal complexes can be directly or indirectly attached to a polymeric backbone, depending on the availability and nature of the reactive groups on the complex and polymer backbone. For example, the pyridine groups in poly(4-vinylpyridine) or the imidazole groups in poly(N-vinylimidazole) are capable of acting as monodentate ligands and thus can be attached to a metal center directly.

15 Alternatively, the pyridine groups in poly(4-vinylpyridine) or the imidazole groups in poly(N-vinylimidazole) can be quaternized with a substituted alkyl moiety having a suitable reactive group, such as a carboxylate function, that can be activated to form a covalent bond with a reactive group, such as an amine, of the transition metal complex. (See Table 1 for a list of other examples of reactive groups.)

20 Redox centers such as, for example, Os^{2+/3+} can be coordinated with five heterocyclic nitrogens and an additional ligand such as, for example, chloride anion. An example of such a coordination complex includes two bipyridine ligands which form stable coordinative bonds, the pyridine of poly(4-vinylpyridine) which forms a weaker coordinative bond, and a chloride anion which forms the least stable 25 coordinative bond.

30 Alternatively, redox centers, such as Os^{2+/3+}, can be coordinated with six heterocyclic nitrogen atoms in its inner coordination sphere. The six coordinating atoms are preferably paired in the ligands, for example, each ligand is composed of at least two rings. Pairing of the coordinating atoms can influence the potential of an electrode used in conjunction with transition metal complex polymers of the present invention.

Typically, for analysis of glucose, the potential at which the working electrode, coated with the redox polymer, is poised is negative of about +250 mV vs. SCE (standard calomel electrode). Preferably, the electrode is poised negative of about +150 mV vs. SCE. Poising the electrode at these potentials reduces the 5 interfering electrooxidation of constituents of biological solutions such as, for example, urate, ascorbate and acetaminophen. The potential can be modified by altering the ligand structure of the complex.

The redox potential of a redox polymer, as described herein, is related to the potential at which the electrode is poised. Selection of a redox polymer with a 10 desired redox potential allows tuning of the potential at which the electrode is best poised. The redox potentials of a number of the redox polymers described herein are negative of about +150 mV vs. SCE and can be negative of about +50 mV vs. SCE in order to allow the poising of the electrode potentials negative of about +250 mV vs. SCE and preferably negative of about +150 mV vs. SCE.

15 The strength of the coordination bond can influence the potential of the redox center in transition metal complex polymers. Typically, the stronger the coordinative bond, the more positive the redox potential. A shift in the potential of a redox center resulting from a change in the coordination sphere of the transition metal can produce a labile transition metal complex. For example, when the redox 20 potential of an Os^{2+/3+} complex is downshifted by changing the coordination sphere, the complex becomes labile. Such a labile transition metal complex may be undesirable when fashioning a metal complex polymer for use as an electron transfer mediator and can be avoided through the use of weakly coordinating multidentate heterocyclics as ligands. When a multidentate ligand is coordinated to the metal ion 25 the amount of energy released is much greater than for a monodentate ligand, hence the complex is more stable even if the individual coordinative bonds are weak.

Electrode Interference

Transition metal complexes used as redox mediators in electrodes can be 30 affected by the presence of transition metals in the analyzed sample including, for example, Fe³⁺ or Zn²⁺. The addition of a transition metal cation to a buffer used to test an electrode results in a decline in the current produced. The degree of current

decline depends on the presence of anions in the buffer which precipitate the transition metal cations. The lesser the residual concentration of transition metal in the sample solution, the more stable the current. Anions which aid in the precipitation of transition metal cations include, for example, phosphate. It has been
5 found that a decline in current upon the addition of transition metal cations is most pronounced in non-phosphate buffers. If an electrode is transferred from a buffer containing a transition metal cation to a buffer free of the transition metal cation, the original current is restored.

The decline in current is thought to be due to additional crosslinking of a
10 pyridine-containing polymer backbone produced by the transition metal cations. The transition metal cations can coordinate nitrogen atoms of different chains and chain segments of the polymers. Coordinative crosslinking of nitrogen atoms of different chain segments by transition metal cations can reduce the diffusivity of electrons.

15 Serum and other physiological fluids contain traces of transition metal ions, which can diffuse into the films of electrodes made with the redox polymers of the present invention, lowering the diffusivity of electrons and thereby the highest current reached at high analyte concentration. In addition, transition metal ions like iron and copper can bind to proteins of enzymes and to the reaction centers or
20 channels of enzymes, reducing their turnover rate. The resulting decrease in sensitivity can be remedied through the use of anions which complex with interfering transition metal ions, for example, in a buffer employed during the production of the metal complex. A non-cyclic polyphosphate such as, for example, pyrophosphate or tripolyphosphate, can be used. For example, sodium or potassium non-
25 cyclic polyphosphate buffers can be used to exchange phosphate anions for those anions in the transition metal complex which do not precipitate transition metal ions. The use of linear phosphates can alleviate the decrease in sensitivity by forming strong complexes with the damaging transition metal ions, assuring that their activity will be low. Other complexing agents can also be used as long as they are
30 not electrooxidized or electroreduced at the potential at which the electrode is poised.

Enzyme Damage and its Alleviation

- Glucose oxidase is a flavoprotein enzyme that catalyzes the oxidation by dioxygen of D-glucose to D-glucono-1,5-lactone and hydrogen peroxide. Reduced transition metal cations such as, for example, Fe^{2+} , and some transition metal complexes, can react with hydrogen peroxide. These reactions form destructive OH radicals and the corresponding oxidized cations. The presence of these newly formed transition metal cations can inhibit the enzyme and react with the metal complex. Also, the oxidized transition metal cation can be reduced by the FADH_2 centers of an enzyme, or by the transition metal complex.
- Inhibition of the active site of an enzyme or a transition metal complex by a transition metal cation, as well as damaging reactions with OH radicals can be alleviated, thus increasing the sensitivity and functionality of the electrodes by incorporating non-cyclic polyphosphates, as discussed above. Because the polyphosphate/metal cation complex typically has a high (oxidizing) redox potential, its rate of oxidation by hydrogen peroxide is usually slow. Alternatively, an enzyme such as, for example, catalase can be employed to degrade hydrogen peroxide.

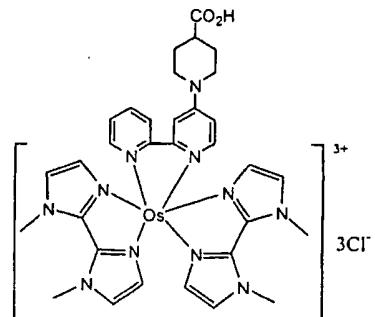
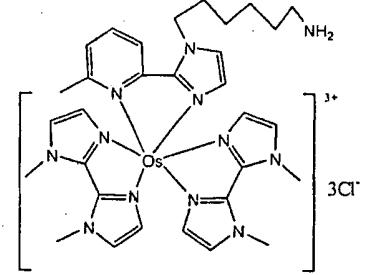
EXAMPLES

Unless indicated otherwise, all of the chemical reagents are available from Aldrich Chemical Co. (Milwaukee, WI) or other sources.

- The synthesis of polymeric transition metal complexes can include the synthesis of a transition metal complex with a reactive group and the subsequent attachment of the complex to a polymeric backbone. In some instances, the polymeric backbone is modified prior to the attachment of the transition metal complex. Synthesis of some transition metal complexes with a reactive group is described in U.S. Patent Application Serial No. _____, entitled "Transition Metal Complexes with Bidentate Ligand having an Imidazole Ring", Attorney Docket No. 12008.41US01, filed on even date herewith, incorporated herein by reference. Examples of suitable transition metal complexes for the present invention are shown in Table 2.

Table 2. Redox Potentials of Selected Transition Metal Complexes

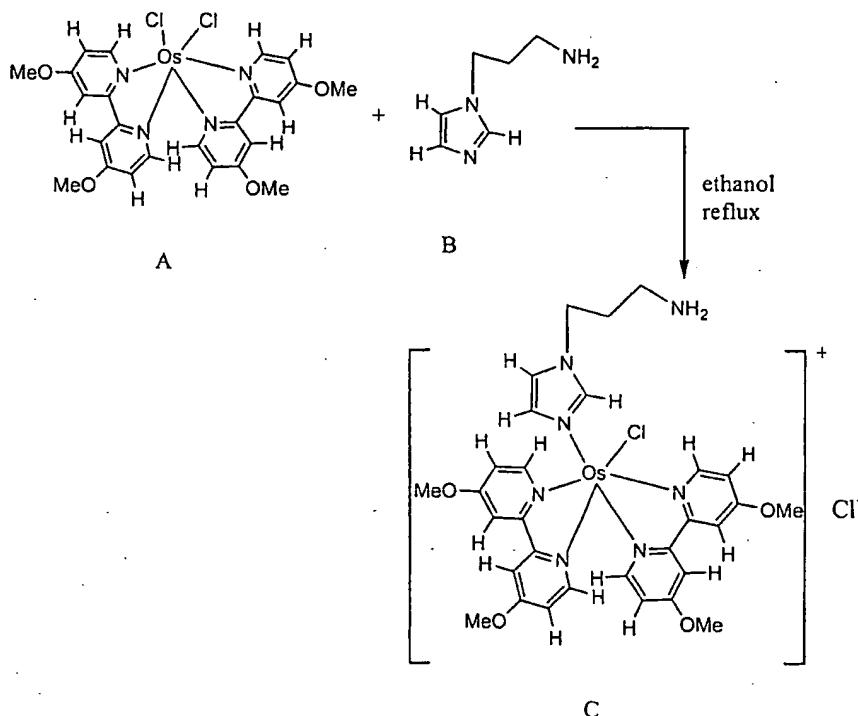
Complex	Structure	$E_{1/2}(\text{vs Ag/AgCl})/\text{mV}^*$
I	<p>[Os(4,4'-dimethoxy-2,2'-bipyridyl)₂(1-(3-aminopropyl)imidazole)]Cl⁺</p>	-102
II	<p>[Os(1,1'-dimethyl-2,2'-biimidazole)₂(4-(6-hydroxyhexyl)amino-2,2'-bipyridine)]Cl₃³⁺</p>	-100
III	<p>[Os(1,1'-dimethyl-2,2'-biimidazole)₂(4-(6-aminohexyl)amino-2,2'-bipyridine)]Cl₃³⁺</p>	-93

<u>IV</u>	 <p><chem>[Os(1,1'-dimethyl-2,2'-biimidazole)2(4-(N-(4-carboxy)piperidino)-2,2'-bipyridine)]Cl3</chem></p>	-60
<u>V</u>	 <p><chem>[Os(1,1'-dimethyl-2,2'-biimidazole)2(1-(6-aminohexyl)-2-(6-methylpyrid-2-yl)imidazole)]Cl3</chem></p>	-81
<p>* Redox potentials were estimated by averaging the positions of the reduction wave peaks and the oxidation wave peaks of cyclic voltammograms (CVs) obtained in pH 7 PBS buffer with a glassy carbon working electrode, a graphite counter electrode and a standard Ag/AgCl reference electrode at a sweep rate of 50 mV/s.</p>		

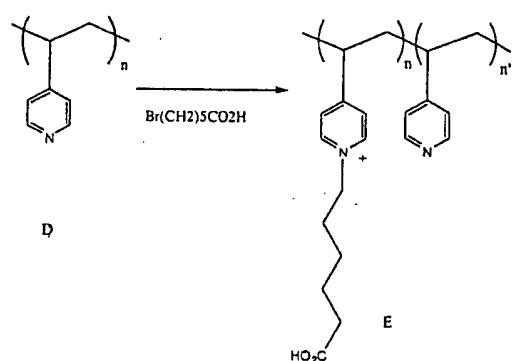
Example 1

Synthesis of [Os(4,4'-dimethoxy-2,2'-bipyridyl)₂(1-(3-aminopropyl)imidazole)Cl₃]:

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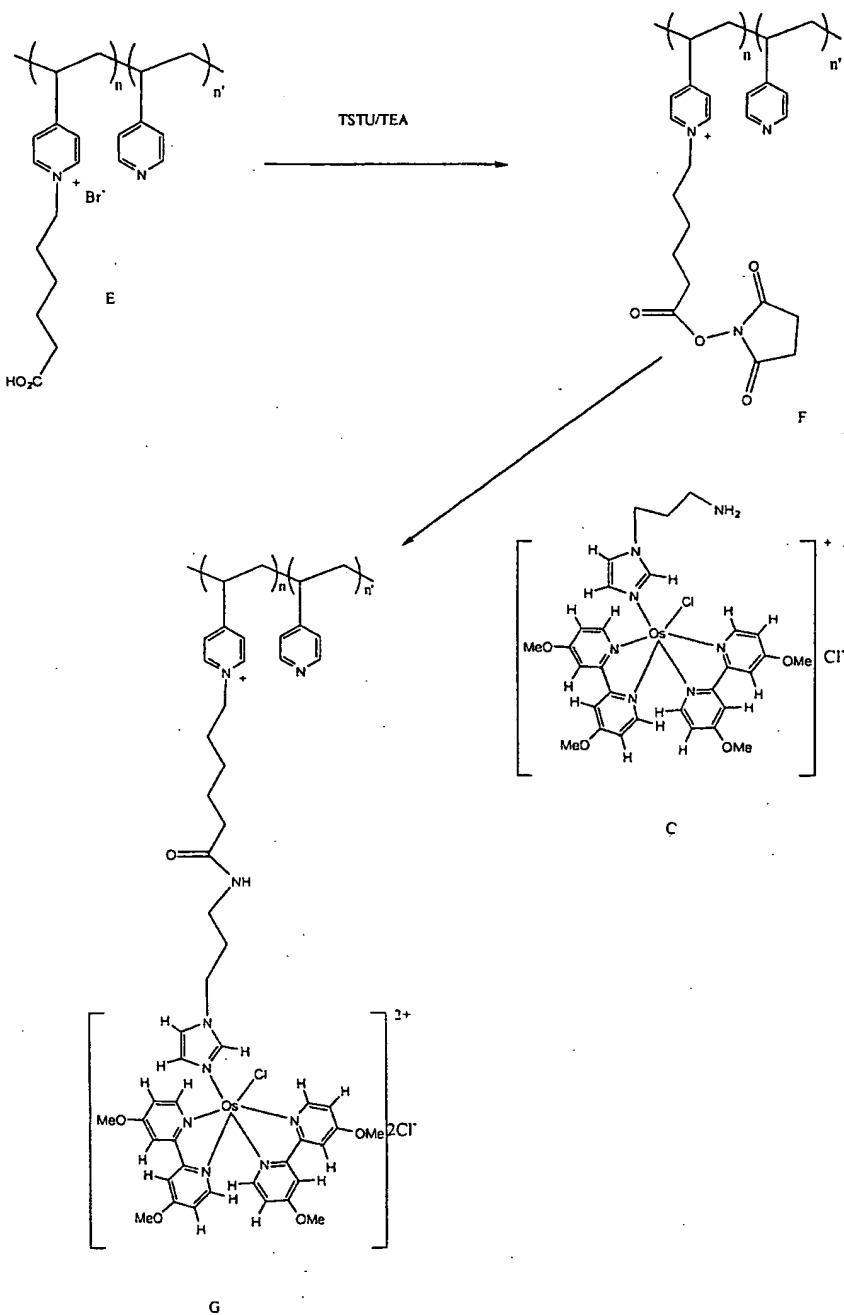


A suspension of compound A (prepared according to U.S. Patent No. 5,393,903, incorporated herein by reference) (1.52g) in 1L anhydrous ethanol in a 3-necked round bottom flask fitted with a reflux condenser was degassed with N₂ for 10 min and then refluxed for 1h. Compound B (259 μL) was added via a syringe over 10 min. and the resulting solution was refluxed for 24 h. The dark brown solution was cooled to room temperature and then concentrated to about 80 mL by rotary evaporation. Ethyl ether (about 400mL) was added and the resulting mixture was degassed for 5 min. After standing at room temperature overnight, the resulting 15 dark brown precipitate of compound C was collected by suction filtration. Yield: about 1g.

Quaternization of Poly(4-vinylpyridine) with 6-Bromohexanoic Acid:

To compound **D** (2g) dissolved in DMF was added 6-bromohexanoic acid (0.56g). The resulting solution was stirred at 90 °C for 24 h. The solution was poured into 200 mL EtOAc under rapid stirring. The precipitate was collected by suction filtration, washed with EtOAc (2x20mL) and then dried under high vacuum at 50 to 60 °C for 2 days. NMR (d_6 -DMSO) indicated that about 15% of the pyridyl groups in the polymer were quaternized. Yield: 2.1g.

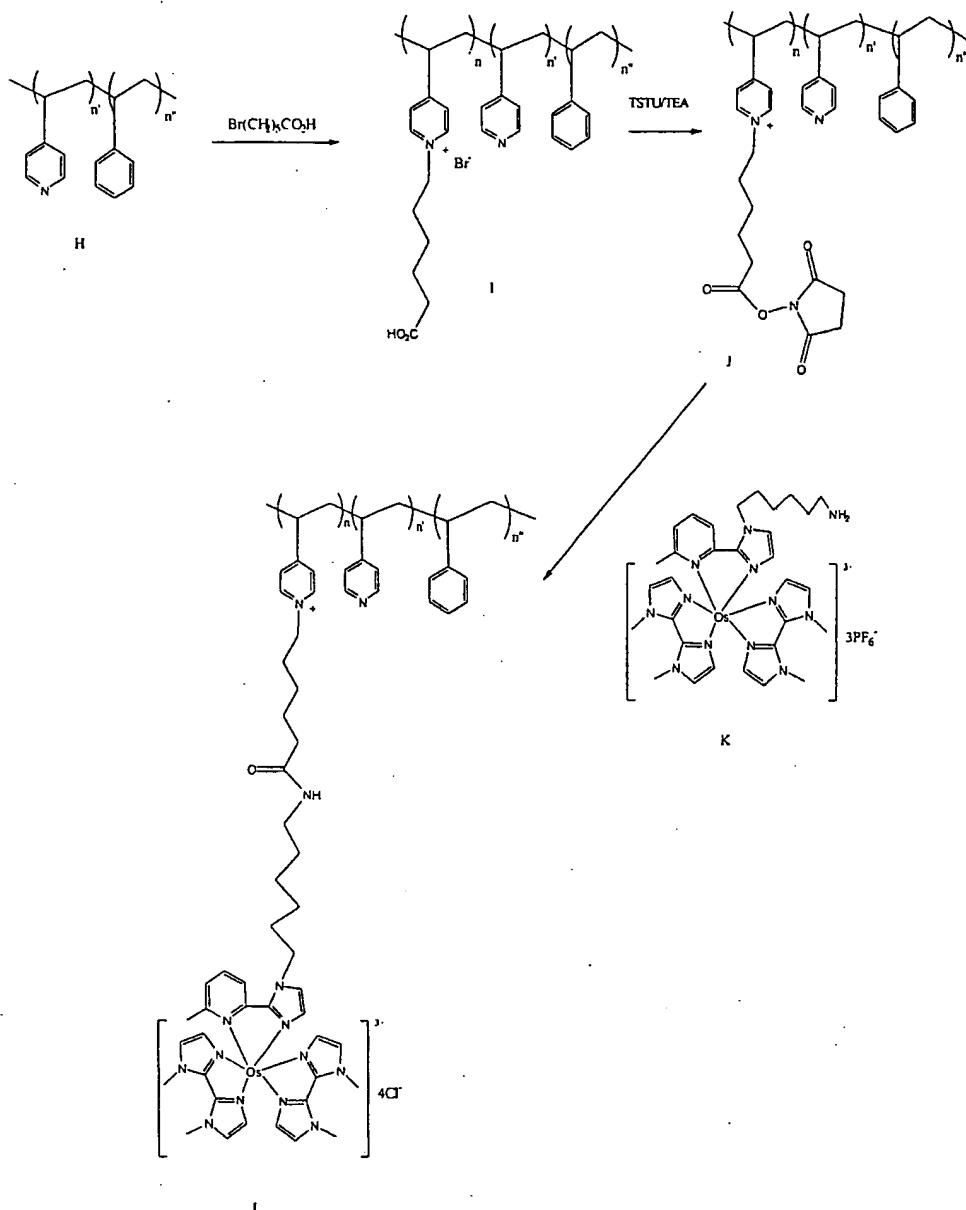
Synthesis of Polymeric Osmium Complex G:



To a solution of compound **E** (71 mg) in 4 mL dry DMF was added *O*-(*N*-succinimidyl)-*N,N,N',N'*-tetramethyluronium tetrafluoroborate (TSTU) (24 mg).

- 5 After the solution was stirred for 30 min, *N,N,N*-diisopropylethylamine (14 μL) was added and the resulting solution was stirred for 4 h. Compound **C** was added at once, followed by addition of another 14 μL *N,N,N*-diisopropylethylamine. The solution

was continued to stir at room temperature for another 24 h. The dark brown solution was poured into 100 mL ether. The precipitate was collected by suction filtration, washed with ether (20 mL) and dried under vacuum at 50 °C for 24 h. The crude product was mixed with 30 mL chloride resin (AG1x4, Bio-Rad Laboratories, Inc.,
5 Hercules, CA) in 50 mL H₂O and the resulting mixture was stirred in open air for 24 h. As the stirring continued, the insoluble polymeric Os(II) complex was slowly oxidized by air to the water soluble polymeric Os(III) complex with chloride as counter anions. The mixture was suction filtered and the filtrate was dialyzed by repeated ultrafiltration with H₂O (ultrafiltration membrane from Millipore, Corp.,
10 Bedford, MA: PM10, NMWL/10,000). The dialyzed polymer concentrate was diluted with H₂O to 10 mL and then freeze-dried to give compound G. Yield: 80 mg.

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Example 2

Synthesis of Compound I: Compound H (10% styrene, Aldrich)(2.37g) was dissolved in DMF (20 mL) by stirring the mixture at 90 °C for 3-4 h. 6-Bromohexanoic acid (0.66g) was added portionwise over 10 min. and the resulting solution was stirred at 90 °C for 24 h. The solution was poured into 300 mL EtOAc and the precipitate was collected by suction filtration. The gummy product was

redissolved in a minimum of methanol and precipitated out with ether (200mL). The product was dried under high vacuum at 50 °C for 2 days.

Synthesis of 2-(6-Methyl-2-pyridyl)imidazole: A solution of 6-methylpyridine-2-carboxaldehyde (26g, 0.21 mole) and glyoxal (40%, 30 mL) in 50 mL EtOH in a three-necked 250 mL round bottom flask fitted with a thermometer and an addition funnel was stirred in a NaCl/ice bath. When the solution was cooled to below 5°C, conc. NH₄OH was added dropwise through the addition funnel. The rate of the addition was controlled so that the temperature of the solution was maintained at below 5°C. After the addition, the stirring of the yellow solution was continued in the ice bath for 1 h and then at room temperature overnight. The light yellow crystals were collected by suction filtration and washed with H₂O (20 mL). The crystals were resuspended in H₂O (200 mL) and boiled briefly, followed by suction filtration, to collect the product which was dried under high vacuum. Yield: 35%.

Synthesis of 2-(6-methyl-2-pyridyl)-1-(6-(phthalimido)hexyl)imidazole: To a solution of 2-(6-Methyl-2-pyridyl)imidazole (2.16g) and sodium t-butoxide (1.57g) in 50 mL dry DMF was added *N*-(6-bromohexyl)phthalimide (4.72g). The resulting solution was stirred at room temperature for 3 h and then at 60°C for 3.5 h. The solution was poured into H₂O (80 mL) and then extracted three times with EtOAc (3x100mL). The combined EtOAc extract was dried with anhydrous Na₂SO₄ and then evaporated to dryness. The product was purified by a silica gel column using EtOAc as the eluent. Yield: about 4.2g.

Synthesis of 1-(6-Aminohexyl)-2-(6-methyl-2-pyridyl)imidazole: To a solution of 2-(6-methyl-2-pyridyl)-1-(6-(phthalimido)hexyl)imidazole (4.2g) in 50 mL EtOH was added 1.5 mL hydrazine hydrate. The resulting solution was stirred at 80 °C overnight. The solution was cooled to room temperature and suction filtered to remove the precipitate. The filtrate was evaporated to give the crude product, which was purified by a silica gel column using 5% conc. NH₃H₂O/CH₃CN as the eluent. Yield: about 2.5g.

Synthesis of 1,1'-Dimethyl-2,2'-biimidazole: To a stirred solution of 2,2'-biimidazole (Fieselmann, B.F., et al. *Inorg. Chem.* 17, 2078(1978)) (4.6g, 34.3 mmoles) in 100 mL dry DMF in a 250 ml round bottom flask cooled in an ice/water

bath was added in portions NaH(60% in mineral oil, 2.7 g, 68.6 mmoles). After the solution was stirred at 0°C for one hour under N₂, methyl toluenesulfonate (10.3 mL, 68.6 mmoles) was added in small portions using a syringe over 30 min. The stirring of the solution in the ice/water bath was continued for 1 h and then at room temperature for 3 h. The solvent was removed by vacuum distillation. The dark residue was triturated with ether and then suction filtered and dried under vacuum. The product was purified by sublimation. Yield: 80%.

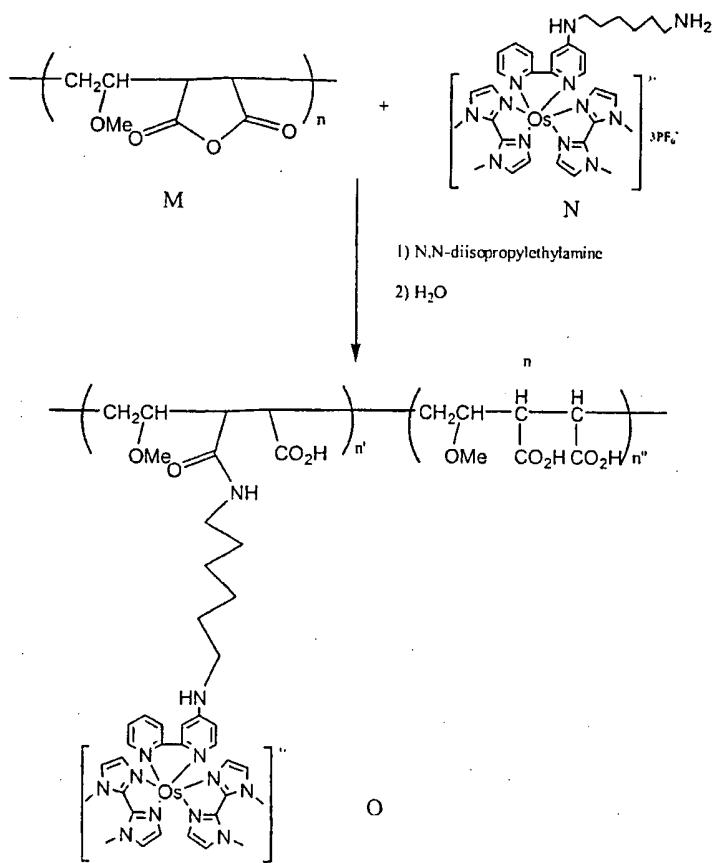
Synthesis of [Os(1,1'-dimethyl-2,2'-biimidazole)₂Cl₂]Cl: Potassium hexachloroosmate (1g, 2.08 mmoles), 1,1'-dimethyl-2,2'-biimidazole (0.67g, 4.16 mmoles) and LiCl (1g, 23.8 mmoles) were suspended in 40 mL ethylene glycol in a 250 mL three-necked round bottom flask fitted with a reflux condenser. The suspension was degassed with N₂ for 15 min and then stirred under N₂ at 170°C in an oil bath for 7-8 h, resulting in a dark brown solution. The solvent was removed by high vacuum distillation at 90-100°C bath temperature. The gummy solid was triturated with acetone twice (2x50mL) and then with H₂O once (50mL). The product was dried at 50°C under high vacuum for 24 h.

Synthesis of Compound K: A mixture of [Os(1,1'-dimethyl-2,2'-biimidazole)₂Cl₂]Cl (0.525g) and 1-(6-aminohexyl)-2-(6-methyl-2-pyridyl)imidazole (0.248g) is 40 mL ethylene glycol was degassed with N₂ for 10 min and then stirred under N₂ at 140° for 24 h. Ethylene glycol was removed by high vacuum distillation at 90°C. The residue was dissolved in 150 mL H₂O and the resulting solution was stirred in open air for 24 h to allow full oxidation of Os(II) to Os(III). The solution was poured into a rapidly stirred solution of NH₄PF₆ (4.2g) in 100 mL H₂O. The precipitate was collected by suction filtration and washed with H₂O (2x10mL). The crude product was redissolved in 15 mL CH₃CN and then added to a stirred solution of NH₄PF₆ (2.2g) in 200 mL H₂O. The resulting precipitate was collected by suction filtration, washed with H₂O (10mL) and then dried under high vacuum at 45°C.

Yield: about 0.6g.

Synthesis of Compound L: the polymeric osmium complex was synthesized from polymer I and complex K using the method described above for compound G.

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Example 3

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Synthesis of 4-bromo-2,2'-bipyridyl-N-oxide: To 4-nitro-2,2'-bipyridyl-N-oxide (Wenkert, D.; Woodward, R.B. *J. Org. chem.* **48**, 283(1983)) (5 g) dissolved in 30 mL acetic acid in a 100 ml round bottom flask was added 16 mL acetyl bromide. The yellow mixture was refluxed for 1.5 h and then rotovaporated to dryness. The resulting light yellow solid was sufficiently pure enough for the next step without further purification. Yield: 95%

Synthesis of 4-bromo-2,2'-bipyridyl: To a stirred suspension of 4-bromo-2,2'-bipyridyl-N-oxide in 60 mL CHCl₃, was added 12 mL PCl₃, at room temperature. The mixture was refluxed for 2 h under N₂ and then cooled to room temperature. The reaction mixture was poured into 100 mL ice/water. The aqueous layer was separated and saved. The CHCl₃ layer was extracted three times with H₂O (3x60 mL) and then discarded. The combined aqueous solution was neutralized with NaHCO₃ powder to about pH 7-8. The resulting white precipitate was collected by suction filtration, washed with H₂O (30 mL) and then dried under vacuum at 50°C for 24 h. Yield: 85%.

Synthesis of a 4-((6-aminohexyl)amino)-2,2'-bipyridine: A mixture of 4-bromo-2,2'-bipyridyl (2.5 g) and 1,6-diaminohexane (15 g) in a 250mL round bottom flask was heated under N₂ at 140°C in an oil bath for 4-5 h. Excess 1,6-diaminohexane was removed by high vacuum distillation at 90-120°C. The product was purified by a silica gel column, eluting with 5% NH₄OH in isopropyl alcohol. Yield: 70%.

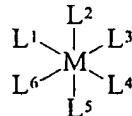
Synthesis of Compound N: Compound N was made from 4-((6-aminohexyl)amino)-2,2'-bipyridine and [Os(1,1'-dimethyl-2,2'-biimidazole)₂Cl₂]Cl using the method described for compound K.

Synthesis of Compound O: To a solution of compound M (37 mg, International Specialty Products, Wayne, NJ, USA) in 2 mL CH₃CN and 0.5 mL THF was added compound N (51 mg), followed by the addition of two drops of N,N,N-diisopropylethylamine. The resulting solution was stirred at room temperature for 24 h. H₂O (5 mL) was added and the solution was stirred for another 24 h. The solution was diluted with more H₂O (50mL) and dialyzed by repeated ultrafiltration as described above for the purification of compound G. The dialyzed solution was freeze-dried to give compound O.

The present invention should not be considered limited to the particular examples described above, but rather should be understood to cover all aspects of the invention as fairly set out in the attached claims. Various modifications, 5 equivalent processes, as well as numerous structures to which the present invention may be applicable will be readily apparent to those of skill in the art to which the present invention is directed upon review of the instant specification.

WHAT IS CLAIMED IS:

1. A polymeric transition metal complex, comprising:
 - a polymeric backbone;
 - a plurality of spacers, each spacer covalently coupled to and extending from the polymeric backbone, each spacer comprising at least one non-cyclic functional group selected from the group consisting of -(CR^s)-, -O-, -S-, -C(O)O-, -S(O)₂NR^k-, -OC(O)NR^m-, -OC(S)NRⁿ, -C(O)NR^l-, -NR^u-, -CR^v=N-O-, -CR^w=NNR^x-, and -(SiR^yR^z)-, wherein R^r and R^s are independently hydrogen, chlorine, fluorine, or substituted or unsubstituted alkyl, alkoxy, alkenyl, or alkynyl and R^k, R^m, Rⁿ, R^l, R^u, R^v, R^w, R^x, R^y, and R^z are independently hydrogen or substituted or unsubstituted alkyl; and
 - a plurality of transition metal complexes, each transition metal complex having the formula:



wherein M is osmium, ruthenium, vanadium, cobalt, or iron;
 L¹ is a ligand comprising a heterocycle and is coordinatively bound to M via a heteroatom of the heterocycle;
 L², L³, L⁴, L⁵, and L⁶ are ligands, wherein each of L¹, L², L³, L⁴, L⁵, and L⁶ is independently a monodentate ligand or combined with at least one other ligand to form a multidentate ligand; and
 wherein at least one of L¹, L², L³, L⁴, L⁵, and L⁶ is covalently coupled to a one of the spacers.

2. The polymeric transition metal complex of claim 1, wherein the heterocycle of L¹ comprises a nitrogen-containing heterocycle and is coordinatively bound to M via a nitrogen atom of the heterocycle.

3. The polymeric transition metal complex of claim 2, wherein the nitrogen-containing heterocycle comprises a substituted or unsubstituted pyridine, imidazole, 2,2'-bipyridine, 2-(2-pyridyl)imidazole, or 2,2'-biimidazole.

4. The polymeric transition metal complex of claim 1, wherein at least three of L², L³, L⁴, L⁵, and L⁶ comprise a nitrogen-containing heterocycle.

5. The polymeric transition metal complex of claim 4, wherein each of L², L³, L⁴, L⁵, and L⁶ comprises a nitrogen-containing heterocycle.

6. The polymeric transition metal complex of claim 1, wherein at least two of L¹, L², L³, L⁴, L⁵, and L⁶ are combined to form at least one multidentate ligand.

7. The polymeric transition metal complex of claim 1, wherein at least four of L¹, L², L³, L⁴, L⁵, and L⁶ are combined to form at least two multidentate ligands.

8. The polymeric transition metal complex of claim 1, wherein at least four of L¹, L², L³, L⁴, L⁵, and L⁶ are combined to form at least two multidentate ligands selected from the group consisting of substituted and unsubstituted 2,2'-bipyridines, 2-(2-pyridyl)imidazoles, and 2,2'-biimidazoles.

9. The polymeric transition metal complex of claim 8, wherein the transition metal complex comprises at least one substituted or unsubstituted 2,2'-biimidazole or 2-(2-pyridyl)imidazole.

10. The polymeric transition metal complex of claim 1, wherein the spacer comprises a flexible chain of at least four atoms.

11. The polymeric transition metal complex of claim 1, wherein the polymeric transition metal complex has a weight average molecular weight of at least 5000.

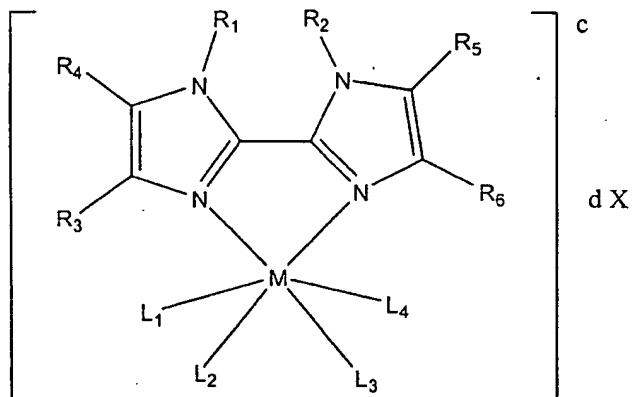
12. The polymeric transition metal complex of claim 1, wherein each spacer comprises at least four non-cyclic functional groups selected from the group consisting of -(CR^R^s)-, -O-, -S-, -S(O)₂NR^k-, -OC(O)NR^m-, -OC(S)NRⁿ-, -C(O)NR^t-, and -NR^u-, wherein R^k, R^m, Rⁿ, R^r, R^s, R^t, and R^u are independently selected from the group consisting of hydrogen and substituted or unsubstituted alkyl.

13. The polymeric transition metal complex of claim 1, wherein each spacer further comprises a heterocycle.

14. The polymeric transition metal complex of claim 13, wherein at least one non-cyclic functional group of the spacer is disposed between the heterocycle of the spacer and the transition metal complex.

15. The polymeric transition metal complex of claim 1, wherein the polymeric transition metal complex has a redox potential negative of +150 mV relative to a Ag/AgCl reference electrode.

16. The polymeric transition metal complex of claim 1, wherein the transition metal complex has the formula:



wherin M is iron, cobalt, ruthenium, osmium, or vanadium;

R₁ and R₂ are independently substituted or unsubstituted alkyl;

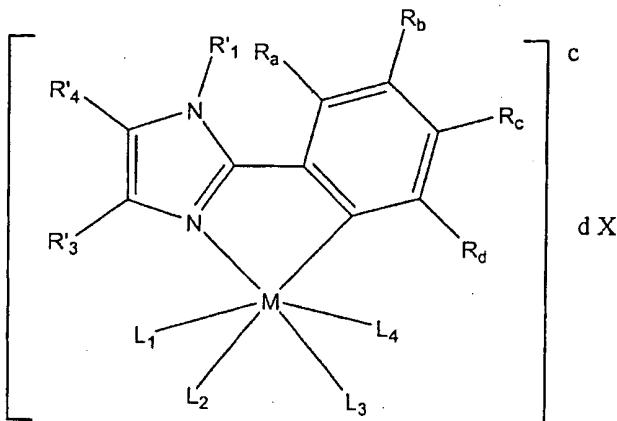
R₃, R₄, R₅, and R₆ are independently -H, -F, -Cl, -Br, or substituted or unsubstituted C1 to C12 alkyl;

c is an integer selected from -1 to -5 or +1 to +5 indicating a positive or negative charge;

X represents at least one counter ion; and

d is an integer from 1 to 5 representing the number of counter ions, X.

17. The polymeric transition metal complex of claim 1, wherein the transition metal complex has the formula:



wherin M is iron, cobalt, ruthenium, osmium, or vanadium;

R'₁ is substituted or unsubstituted alkyl;

R'₃ and R'₄ are independently -H, -F, -Cl, -Br, or substituted or unsubstituted C1 to C12 alkyl;

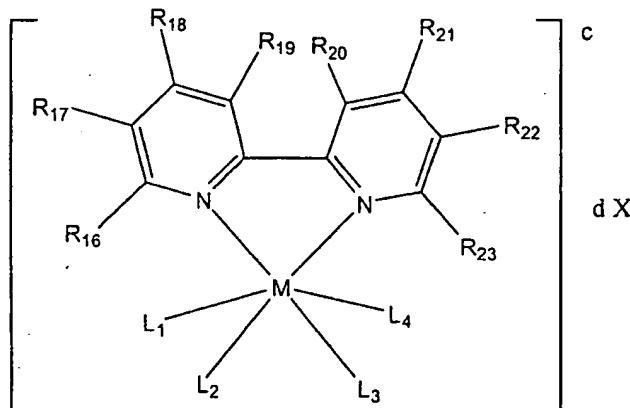
R_a, R_b, R_c and R_d are independently -H, -F, -Cl, -Br, -CN, -CO₂H, -SO₃H, -NO₂, -NH₂, -NHNH₂, -SH, or substituted or unsubstituted C1 to C12 alkylamino, C2 to C24 dialkylamino, C1 to C12 alkoxy, or C1 to C12 alkyl;

c is an integer selected from -1 to -5 or +1 to +5 indicating a positive or negative charge;

X represents at least one counter ion; and

d is an integer from 1 to 5 representing the number of counter ions, X.

18. The polymeric transition metal complex of claim 1, wherein the transition metal complex has the formula:



wherein M is iron, cobalt, ruthenium, osmium, or vanadium;

R₁₈ and R₂₁ are independently -H, -F, -Cl, -Br, -CN, -CO₂H, -OH, -SO₃H, -

NO₂, -NH₂, -NHNH₂, -SH, or substituted or unsubstituted C1 to C12

alkylamino, C2 to C24 dialkylamino, C1 to C12 alkoxy, or C1 to C12 alkyl

R₁₆, R₁₇, R₁₉, R₂₀, R₂₂ and R₂₃ are independently -H, or substituted or

unsubstituted C1 to C12 alkyl;

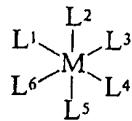
c is an integer selected from -1 to -5 or +1 to +5 indicating a positive or negative charge;

X represents at least one counter ion; and

d is an integer from 1 to 5 representing the number of counter ions, X.

19. A polymeric transition metal complex, comprising a reaction product of

- a) a polymer comprising a polymeric backbone and a plurality of pendant groups extending from the polymeric backbone, wherein at least a portion of the pendant groups comprise a reactive group; and
- b) a plurality of transition metal complexes, each transition metal complex having the formula:



wherein M is osmium, ruthenium, vanadium, cobalt, or iron;

L¹ is a ligand comprising a heterocycle and is coordinatively bound to M via a heteroatom of the heterocycle;

L², L³, L⁴, L⁵, and L⁶ are ligands, wherein each of L¹, L², L³, L⁴, L⁵, and L⁶ is independently a monodentate ligand or combined with at least one other ligand to form a multidentate ligand; and

wherein at least one of L¹, L², L³, L⁴, L⁵, and L⁶ comprises a reactive group that is capable of reacting with one of the reactive groups of the polymer.

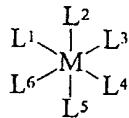
20. The polymeric transition metal complex of claim 19, wherein a portion of the pendant groups are not coupled to the transition metal complex.

21. A polymeric transition metal complex, comprising:

a polymeric backbone;

a plurality of spacers, each spacer covalently coupled to and extending from the polymeric backbone, each spacer comprising a flexible chain of at least four atoms;

a plurality of transition metal complexes, each transition metal complex having the formula:



wherein M is osmium, ruthenium, vanadium, cobalt, or iron;

L¹ is a ligand comprising a heterocycle and is coordinatively bound to M via a heteroatom of the heterocycle;

L^2 , L^3 , L^4 , L^5 , and L^6 are ligands, wherein each of L^1 , L^2 , L^3 , L^4 , L^5 , and L^6 is independently a monodentate ligand or combined to form one or more multidentate ligands; and

wherein at least one of L^1 , L^2 , L^3 , L^4 , L^5 , and L^6 is covalently coupled to a one of the spacers.

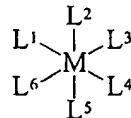
22. The polymeric transition metal complex of claim 21, wherein the flexible chain is a flexible chain of at least eight atoms.

23. A redox mediator, comprising:

a polymeric backbone;

a plurality of spacers, each spacer covalently coupled to and extending from the polymeric backbone, each spacer comprising at least one non-cyclic functional group selected from the group consisting of $-(CR^sR^s)-$, $-O-$, $-S-$, $-C(O)O-$, $-S(O)_2NR^k-$, $-OC(O)NR^m-$, $-OC(S)NR^n-$, $-C(O)NR^l-$, $-NR^u-$, $-CR^v=N-O-$, $-CR^w=NNR^x-$, and $-(SiR^yR^z)-$, wherein R^r and R^s are independently hydrogen, chlorine, fluorine, or substituted or unsubstituted alkyl, alkoxy, alkenyl, or alkynyl and R^k , R^m , R^n , R^l , R^u , R^v , R^w , R^x , R^y , and R^z are independently hydrogen or substituted or unsubstituted alkyl;

a plurality of transition metal complexes, each transition metal complex having the formula:



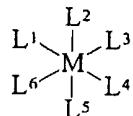
wherein M is osmium, ruthenium, vanadium, cobalt, or iron;

L^1 is a ligand comprising a heterocycle and is coordinatively bound to M via a heteroatom of the heterocycle;

L^2 , L^3 , L^4 , L^5 , and L^6 are ligands, wherein each of L^1 , L^2 , L^3 , L^4 , L^5 , and L^6 is independently a monodentate ligand or combined with at least one other ligand to form a multidentate ligand; and

wherein at least one of L^1 , L^2 , L^3 , L^4 , L^5 , and L^6 is covalently coupled to a one of the spacers.

24. A sensor comprising:
- a working electrode;
 - a counter electrode; and
 - a redox mediator disposed proximate to the working electrode, the redox mediator comprising
 - a polymeric backbone,
 - a plurality of spacers, each spacer covalently coupled to and extending from the polymeric backbone, each spacer comprising at least one non-cyclic functional group selected from the group consisting of -(CR^rR^s)-, -O-, -S-, -C(O)O-, -S(O)₂NR^k-, -OC(O)NR^m-, -OC(S)NRⁿ-, -C(O)NR^t-, -NR^u-, -CR^v=N-O-, -CR^w=NNR^x-, and -(SiR^yR^z)-, wherein R^r and R^s are independently hydrogen, chlorine, fluorine, or substituted or unsubstituted alkyl, alkoxy, alkenyl, or alkynyl and R^k, R^m, Rⁿ, R^t, R^u, R^v, R^w, R^x, R^y, and R^z are independently hydrogen or substituted or unsubstituted alkyl;
 - a plurality of transition metal complexes, each transition metal complex having the formula:



wherein M is osmium, ruthenium, vanadium, cobalt, or iron,
 L¹ is a ligand comprising a heterocycle and is coordinatively bound to
 M via a heteroatom of the heterocycle,

L², L³, L⁴, L⁵, and L⁶ are ligands, wherein each of L¹, L², L³, L⁴, L⁵, and L⁶ is independently a monodentate ligand or combined with at least one other ligand to form a multidentate ligand, and

wherein at least one of L¹, L², L³, L⁴, L⁵, and L⁶ is covalently coupled to a one of the spacers.

25. The sensor of claim 24, wherein at least four of L¹, L², L³, L⁴, L⁵, and L⁶ are combined to form at least two multidentate ligands selected from the group

consisting of substituted and unsubstituted 2,2'-bipyridines, 2-(2-pyridyl)imidazoles, and 2,2'-biimidazoles.

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